AERONAUTICS

FIFTH ANNUAL REPORT

OF THE

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

1919

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MESSAGE OF THE PRESIDENT.

To the Senate and House of Representatives:

In compliance with the provisions of the act of March 3, 1915, making appropriations for the naval service for the fiscal year ending June 30, 1916, I transmit herewith the fifth annual report of the National Advisory Committee for Aeronautics for the fiscal year ended June 30, 1919.

The attention of the Congress is invited to the suggestion of the committee that the appendixes of the report be published with the report as a public document; and to the recommendations of the committee in the closing paragraphs of the report, which have my approval.

WOODROW WILSON.

THE WHITE HOUSE,
5 December, 1919.

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LETTER OF SUBMITTAL.

National Advisory Committee for Aeronautics,
D–433, Fourth Street and Missouri Avenue NW.,
Washington, D. C., December 2, 1919.

The President:

In compliance with the provisions of the act of Congress, approved March 3, 1915 (naval appropriation act, Public, No. 273, 63d Cong.), the National Advisory Committee for Aeronautics has the honor to submit herewith its fifth annual report, including a statement of its expenditures for the fiscal year ending June 30, 1919.

Attention is invited to the appendixes to the committee's report, comprising technical reports Nos. 51 to 82, inclusive, and it is recommended that they be published as a public document, complete with illustrations, and as a part of the annual report of the committee.

Your attention is especially invited to the "Conclusion" of the report. The committee trusts that its recommendations, especially those enumerated in the closing paragraphs of the report, may have your approval.

Very respectfully,

National Advisory Committee for Aeronautics,
Charles D. Walcott, *Chairman.*

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

Fourth Street and Missouri Avenue,

WASHINGTON, D. C.

Dr. CHARLES D. WALCOTT, *Chairman*,
Secretary, Smithsonian Institution, Washington, D. C.
Dr. S. W. STRATTON, *Secretary*,
Bureau of Standards, Washington, D. C.
Dr. JOSEPH S. AMES, *Chairman Executive Committee*,
Johns Hopkins University, Baltimore, Md.
Col. THURMAN H. BANE, U. S. Army,
Engineering Division, Air Service, Dayton, Ohio.
Capt. T. T. CRAVEN, U. S. Navy, *Director, Naval Aviation*,
Navy Department, Washington, D. C.
Dr. WILLIAM F. DURAND,
Leland Stanford Junior University, California.
Dr. JOHN F. HAYFORD,
Northwestern University, Evanston, Ill.
Prof. CHARLES F. MARVIN,
Chief, United States Weather Bureau, Washington, D. C.
Maj. Gen. CHARLES T. MENOHER, U. S. Army,
Director of Air Service, Washington, D. C.
Dr. MICHAEL I. PUPIN,
Columbia University, New York City.
Rear Admiral D. W. TAYLOR, U. S. Navy,
Navy Department, Washington, D. C.

EXECUTIVE COMMITTEE.

Dr. JOSEPH S. AMES, *Chairman*.
Dr. S. W. STRATTON, *Secretary*.

Col. THURMAN H. BANE, U. S. Army.
Capt. T. T. CRAVEN, U. S. Navy.
Dr. JOHN F. HAYFORD.
Maj. Gen. CHARLES T. MENOHER, U. S. Army.
Rear Admiral D. W. TAYLOR, U. S. Navy.
Dr. CHARLES D. WALCOTT.

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FIFTH ANNUAL REPORT OF THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

National Advisory Committee for Aeronautics,
D–433, Fourth Street and Missouri Avenue NW.,
Washington, D. C., December 1, 1919.

To the Congress:

In accordance with the provisions of the act of Congress approved March 3, 1915, establishing the National Advisory Committee for Aeronautics, the committee submits herewith its fifth annual report. This report reviews the activities of the committee during the past year, the work accomplished in the study of scientific problems relating to aeronautics, the assistance rendered by the committee in the examination of aeronautical inventions, and in the collection and distribution of scientific and technical data, and contains a statement of expenditures, estimates for the fiscal year 1921, and certain recommendations for the consideration of Congress. Technical reports covering the various subjects under investigation during the past year are submitted as appendixes.

FUNCTIONS OF THE COMMITTEE.

The National Advisory Committee for Aeronautics was established by Congress by act approved March 3, 1915. Under the law the committee is charged with the supervision and direction of the scientific study of the problems of flight with a view to their practical solution, the determination of the problems which should be experimentally attacked, their investigation and application to practical questions of aeronautics. The committee is also authorized to direct and conduct research and experiment in aeronautics in such laboratory or laboratories, in whole or in part, as may be placed under its direction.

Supplementing the prescribed duties of the committee, its broad general functions may be stated as follows:

First. Under the law the committee holds itself at the service of any department or agency of the Government interested in aeronautics for the furnishing of information or assistance in regard to scientific or technical matters relating to aeronautics, and in particular for the investigation and study of problems in this field with a view to their practical solution.

Second. The committee may also exercise its functions for any individual, firm, association, or corporation within the United States, provided that such individual, firm, association, or corporation defray the actual cost involved.

Third. The committee institutes research, investigation, and study of problems which, in the judgment of its members or of the members of its various subcommittees, are needful and timely for the advance of the science and art of aeronautics in its various branches.

Fourth. The committee keeps itself advised of the progress made in research and experimental work in aeronautics in all parts of the world, particularly in England, France, and Italy, and will extend its efforts to the securing of information from Germany, Austria, Canada, and other countries.

Fifth. The information thus gathered is brought to the attention of the various subcommittees for consideration in connection with the preparation of programs for research and experimental work in this country. This information is also made available promptly to the military and naval air services and other branches of the Government, university laboratories, and aircraft manufacturers interested in the study of specific problems.

Sixth. The committee holds itself at the service of the President, the Congress, and the executive departments of the Government for the consideration of special problems which may be referred to it, such as rules for international air navigation, regulation and development of civil aerial transport, technical development policies of the military, naval, and postal air services.

ORGANIZATION OF THE COMMITTEE.

The committee has 12 members, appointed by the President as authorized by Congress. The personnel of the committee consists of two members from the War Department, from the office in charge of military aeronautics; two members from the Navy Department, from the office in charge of naval aeronautics; a representative each of the Smithsonian Institution, of the United States Weather Bureau, and of the United States Bureau of Standards, and not more than five additional persons acquainted with the needs of aeronautical science, either civil or military, or skilled in aeronautical engineering or allied sciences.

During the past year Maj. Gen. William L. Kenly, Director of Military Aeronautics, and Dr. Wallace C. Sabine, of the Bureau of Aircraft Production, were succeeded on the committee by Maj. Gen. Charles T. Menoher, Director of Air Service, and Col. Thurman H. Bane, Chief of the Engineering Division of the Air Service. Commander John H. Towers, United States Navy, was succeeded on the committee by Capt. T. T. Craven, United States Navy, Director of Naval Aviation. Dr. John R. Freeman resigned and his successor has not yet been appointed.

The full committee meets twice a year, the annual meeting being held in October and the semiannual meeting in April. The present report includes the activities of the committee between the annual meeting held on October 10, 1918, and that held on October 9, 1919.

The present organization of the committee is as follows:

Charles D. Walcott, Sc. D., chairman.
S. W. Stratton, Sc. D., secretary.
Joseph S. Ames, Ph. D.
Col. Thurman H. Bane, United States Army.
Capt. T. T. Craven, United States Navy.
William F. Durand, Ph. D.
John F. Hayford, C. E.
Charles F. Marvin, M. E.
Maj. Gen. Charles T. Menoher, United States Army.
Michael I. Pupin, Ph. D.
Rear Admiral D. W. Taylor, United States Navy.

AMENDMENTS TO REGULATIONS.

At the annual meeting held on October 9, 1919, amendments to the regulations were adopted which provided officially for the position of executive officer, and in accordance therewith Prof. George W. Lewis was appointed executive officer.

THE EXECUTIVE COMMITTEE.

For carrying out the work of the Advisory Committee the regulations provide for the election annually of an executive committee, to consist of seven members, and to include further any member of the Advisory Committee not otherwise a member of the executive committee, but resident in or near Washington and giving his time wholly or chiefly to the special work of the committee. The executive committee, as elected and organized on October 9, 1919, is as follows:

Joseph S. Ames, Ph. D., chairman.
S. W. Stratton, Sc. D., secretary.
Col. Thurman H. Bane, United States Army.
Capt. T. T. Craven, United States Navy.
John F. Hayford, C. E.
Charles F. Marvin, M. E.
Maj. Gen. Charles T. Menoher, United States Army.
Rear Admiral D. W. Taylor, United States Navy.
Charles D. Walcott, Sc. D.

The executive committee, in accordance with the general instructions of the Advisory Committee, controls the administration of the affairs of the committee and exercises general supervision over all arrangements for research and other matters undertaken or promoted by the Advisory Committee.

The executive committee held regular monthly meetings throughout the year, and in addition held five special meetings on the following dates:

October 10, October 30, and December 2, 1918; February 21 and August 14, 1919.

The committee has organized the necessary clerical and technical staffs for handling the work of the committee proper, all of which is performed under the personal supervision of one or more of the officers of the committee. The assistant secretary, who also serves as special disbursing agent, has charge of the office, records, and property of the committee.

SUBCOMMITTEES, FUNCTIONS AND ORGANIZATION.

On May 20, 1919, pursuant to instructions of the Advisory Committee, the executive committee discharged all the subcommittees as established for the war emergency, and established new subcommittees, with functions and organization clearly defined, as shown below. Under provision of the regulations for the conduct of the work of the committee, the membership of subcommittees is not limited to members of the Advisory Committee.

COMMITTEE ON AERODYNAMICS.

FUNCTIONS.

1. To aid in determining the problems relating to the theoretical and experimental study of aerodynamics to be experimentally attacked by governmental and private agencies.

2. To endeavor to coordinate, by counsel and suggestion, the research and experimental work involved in the investigation of such problems.

3. To act as a medium for the interchange of information regarding aerodynamic investigations in progress or proposed.

4. The committee may direct and conduct research and experiment in aerodynamics in such laboratory or laboratories, either in whole or in part, as may be placed under its direction.

5. The committee shall meet from time to time on call of the chairman, and report its actions and recommendations to the executive committee.

ORGANIZATION.

Dr. John F. Hayford, chairman.
Dr. Joseph S. Ames, vice chairman.
Prof. Charles F. Marvin.
Col. T. H. Bane, United States Army.
Lieut. Col. V. E. Clark, United States Army.
Dr. A. F. Zahm.
Commander J. C. Hunsaker, United States Navy.
Dr. L. J. Briggs.
M. D. Hersey.
E. P. Warner, secretary.

COMMITTEE ON POWER PLANTS FOR AIRCRAFT.

FUNCTIONS.

1. To aid in determining the problems relating to power plants for aircraft to be experimentally attacked by governmental and private agencies.

2. To endeavor to coordinate, by counsel and suggestion, the research and experimental work involved in the investigation of such problems.

3. To act as a medium for the interchange of information regarding aeronautic power plant investigations, in progress or proposed.

4. The committee may direct and conduct research and experiment on aeronautic power plant problems in such laboratory or laboratories, either in whole or in part, as may be placed under its direction.

5. The committee shall meet from time to time on call of the chairman, and report its actions and recommendations to the executive committee.

ORGANIZATION.

Dr. W. S. Stratton, chairman.
L. M. Griffith.
Prof. George W. Lewis.
Maj. George E. A. Hallett, United States Army.
J. G. Vincent.
Harvey N. Davis.
Herbert Chase.
Commander Arthur K. Atkins, United States Navy.
Dr. H. C. Dickinson, acting secretary.

COMMITTEE ON MATERIALS FOR AIRCRAFT.

FUNCTIONS.

1. To aid in determining the problems relating to materials for aircraft to be experimentally attacked by governmental and private agencies.

2. To endeavor to coordinate, by counsel and suggestion, the research and experimental work involved in the investigation of such problems.

3. To act as a medium for the interchange of information regarding investigations of materials for aircraft, in progress or proposed.

4. The committee may direct and conduct research and experiment on materials for aircraft in such laboratory or laboratories, either in whole or in part, as may be placed under its direction.

5. The committee shall meet from time to time on call of the chairman, and report its actions and recommendations to the executive committee.

ORGANIZATION.

Dr. S. W. Stratton, chairman.
Dr. G. K. Burgess, vice chairman.
Lieut. Col. H. C. K. Muhlenberg, United States Army.
Commander J. C. Hunsaker, United States Navy.
H. L. Whittemore, acting secretary.

COMMITTEE ON PERSONNEL, BUILDINGS, AND EQUIPMENT.

FUNCTIONS.

1. To handle all matters relating to personnel, including the employment, promotion, discharge, and duties of all employees and others assigned to the committee for duty.

2. To consider questions referred to it and initiate projects concerning the erection or alteration of buildings and the equipment of buildings, offices, houses, etc.

3. To meet from time to time on the call of the chairman, and report its actions and recommendations to the executive committee.

4. To supervise such construction and equipment work as may be authorized by the executive committee.

ORGANIZATION.

Dr. Joseph S. Ames, chairman.
Dr. S. W. Stratton, vice chairman.
Prof. Charles F. Marvin.
J. F. Victory, secretary.

COMMITTEE ON PUBLICATIONS AND INTELLIGENCE.

FUNCTIONS.

1. The collection, classification, and diffusion of technical knowledge on the subject of aeronautics, including the results of research and experimental work done in all parts of the world.
2. The encouragement of the study of the subject of aeronautics in institutions of learning.
3. Supervision of the office of aeronautical intelligence.
4. Supervision of the foreign office in Paris.
5. The collection and preparation for publication of the annual report and its appendixes.

ORGANIZATION.

Dr. Joseph S. Ames, chairman.
Prof. Charles F. Marvin, vice chairman.
Miss M. M. Muller, secretary.

COMMITTEE ON GOVERNMENTAL RELATIONS.

FUNCTIONS.

1. Relations of the committee with executive departments and other branches of the Government.
2. Governmental relations with civil agencies.

ORGANIZATION.

Dr. Charles D. Walcott, chairman.
Dr. S. W. Stratton.
J. F. Victory, secretary.

QUARTERS FOR COMMITTEE.

During the fiscal year ended June 30, 1919, the administrative offices of the National Advisory Committee for Aeronautics were located in the Air Service Building, Fourth Street and Missouri Avenue NW., Washington, D. C. The technical work of the committee, conducted by or under the supervision of the various subcommittees, was carried on in various laboratories and shops belonging to the Government, including the Bureau of Standards and the committee's own field station at Langley Field, Va., and also in various laboratories connected with institutions of learning whose cooperation in the conduct of scientific research in aeronautics had been secured.

THE FIELD STATION.

The committee's field station as a whole comprises a research laboratory, an aerodynamical laboratory, and an engine dynamometer laboratory, all of which buildings have been erected by the committee on a tract at Langley Field, Va., known as plot 16, which was set aside for the committee's use by the Chief Signal Officer of the Army in 1916. Its use by the committee was officially approved by the Acting Secretary of War on April 24, 1919.

Langley Field was selected as the site for the conduct of the committee's research work at a time when it was the intention of the Army and Navy authorities to concentrate all research and experimental work in aeronautics at Langley Field. The Navy subsequently secured a site of its own on the other side of Chesapeake Bay, but the Army and the committee proceeded with their original plans for the use of Langley Field. Owing to war pressure, however, the experimental work of the Army was early moved to McCook Field, Dayton, Ohio, and Langley Field was used primarily during the war as a training school for aviators.

The Army intends to continue its experimental work at Dayton, and to use Langley Field as a training and coast defense station and for experimental development work on airships.

Added to these circumstances are other considerations, of minor importance when taken singly, but collectively forming a compelling reason for the committee to recommend, after

careful deliberation, that Congress authorize the removal of its activities from Langley Field, Va., to Bolling Field, D. C. The committee belives it uneconomical and unsatisfactory to remain at Langley Field. The same work can be carried on more efficiently, more promptly, and more economically at Bolling Field, where the work can be more closely watched by all members of the committee, and where the members of the engineering staff in charge of work can have ready access to the committee, to large libraries and other sources of information, constant communication with the Bureau of Standards, a more satisfactory market for labor and supplies and adequate power supply, and relief from the perplexing question of securing quarters at Langley Field or in Hampton or other near-by towns. Much direct effort is wasted in striving to accomplish results in the face of the difficulties encountered at Langley Field The Army's plans for the development of Langley Field as a coast defense station will require its use of the entire field and its facilities. The Army Air Service and the Naval Air Service are in accord with the committee in strongly recommending that Congress authorize the removal of the committee's research activities and the equipment used in connection therewith to Bolling Field, the disposal of the committee's buildings at Langley Field to the Air Service of the Army, and the erection of the necessary permanent buildings at Bolling Field. There is an immense advantage to be gained from the conduct of scientific work in a center of education and learning, and where it would be possible to confer with visiting scientists. Work conducted at Bolling Field would also have the advantage of being accessible to Members of Congress.

THE RESEARCH LABORATORY.

The research laboratory at Langley Field, Va., is the headquarters of the committee's field station. It is a permanent brick building, containing small, well-equipped woodworking and machine shops, photographic and instrument laboratories, and offices of the clerical and drafting force of the field station. The principal work of the research laboratory as a unit is to serve the needs of the aerodynamical laboratory and the engine dynamometer laboratory, in which the actual tests and experimental work are conducted.

THE AERODYNAMICAL LABORATORY.

In addition to the facilities for instrument, machine, and photographic work housed in the research laboratory building, the aerodynamical laboratory consists of a 5-foot wind tunnel located in a specially constructed permanent wind tunnel building. The wind tunnel has been completed but is not yet in operation, due to lack of power. The Army's power plant at Langley Field has not been completed, and no work is being done on same, due to lack of funds. The power company of the city of Hampton is unable to furnish the necessary power. The committee proposes to install a 200 to 300 horsepower electric dynamometer to furnish direct current temporarily. This dynamometer will be operated by a Liberty engine, and will be converted to its proper laboratory work as soon as other means of securing power can be obtained. Reference to the work of the aerodynamical laboratory, which includes the testing of the performance of airplanes in full flight, is made in another part of this report under the "Report of the Committee on Aerodynamics."

THE ENGINE DYNAMOMETER LABORATORY.

The engine dynamometer laboratory is at present temporarily housed in a four-section steel airplane hangar, erected during the past year. The major items of the present equipment consists of one 300 to 400 horsepower electric dynamometer, one 40 to 75 horsepower electric dynamometer, and one 2½ horsepower bench electric dynamometer. The two larger machines are completely equipped with auxiliary apparatus sufficient to obtain all the data necessary for standard tests, as well as that necessary in connection with the special investigations now in progress or contemplated in the immediate future. Operation of this equipment has been prevented by lack of power, but it is expected that this difficulty will shortly be overcome in the manner mentioned in the description of the aerodynamical laboratory. Samples of domestic and foreign aircraft engines have been assembled at the engine dynamometer laboratory for

study and test. The laboratory will furnish temporarily the power for its own operation and for the operation of the aerodynamical laboratory, pending the erection of the Army's power plant.

OFFICE OF AERONAUTICAL INTELLIGENCE.

The Office of Aeronautical Intelligence has continued its work of collecting, analyzing, classifying, and disseminating scientific reports and technical data on aeronautical subjects. The work is conducted under the personal supervision of Dr. Joseph S. Ames, member of the committee, acting also as Director of the Office of Aeronautical Intelligence.

The general policy of the office is not only to make available to all who are properly interested the results of recent developments in aeronautics, scientific reports, and technical data secured from many sources, but also to bring such material to their attention in an appropriate manner.

The different reports received from outside sources during the past year numbered approximately 2,300. Many of these were copied in the office for distribution, others were filed for reference only, and the remainder, because they were too large to copy, were circulated on loan. The records of the office show that copies of technical reports were distributed among various agencies as follows:

Field station, National Advisory Committee for Aeronautics	502
Paris office, National Advisory Committee for Aeronautics	678
Air Service of the Army	1,319
Naval Air Service	946
Miscellaneous governmental agencies	503
Aircraft manufacturers	1,247
Educational institutions	352
Private individuals, unattached	160
Foreign distribution	1,734
Total	7,441

The above figures do not include the distribution of technical reports printed by the committee with its annual reports. They refer only to reports of which duplicates were made available by typewriting, blue printing, photostating, etc.

The Paris office of the National Advisory Committee for Aeronautics was opened in June, 1919, for the purpose of securing by exchange scientific reports and technical data in European countries, particularly England, France, and Italy, and its administration was placed under the Office of Aeronautical Intelligence.

THE PARIS OFFICE.

On May 20, 1919, the committee authorized the establishment of a foreign office with headquarters in Paris, to be under the general supervision of the Committee on Publications and Intelligence and under the immediate supervision of a technical assistant in Europe. Arrangements were made with the State Department to have the technical assistant in Europe to the National Advisory Committee for Aeronautics accredited officially to the Governments of Great Britain, France, and Italy.

The Paris office of the committee was opened in June, 1919, with Mr. William Knight, M. E., in charge. The general functions of the Paris office are to collect and exchange reports, data, and miscellaneous information of a purely technical and scientific nature relating to aeronautics; to translate this information, and to prepare abstracts of important articles relating to aeronautics appearing in European scientific publications. The technical reports and information collected by the Paris office are transmitted to the Office of Aeronautical Intelligence for distribution in this country.

It is also a function of the technical assistant in charge of the Paris office to secure special information for American military and naval attachés or for special air service representatives on request; to keep in close touch with the scientific research in progress, particularly at the St. Cyr Aerodynamic Laboratory, in France, the National Physical Laboratory, in England, and the Instituto Centrale Aeronautico, in Italy, and visit Italy and England once or twice a year to gather the latest information.

INTERNATIONAL AIR NAVIGATION.

Under date of December 18, 1918, the committee reported to the President that the expected development of commercial aviation would make it exceedingly desirable that certain fundamental principles be agreed upon at the peace conference in relation to international air navigation and at that time suggested certain principles for consideration.

In March, 1919, the committee received through the State Department a copy of proposed regulations for international air navigation prepared by the Inter-Ministerial Commission of Civil Aeronautics appointed by the peace conference at Paris. The committee at that time was not asked to comment on the terms of the document. It did, however, report to the President that certain minor changes in the use of technical terms were advisable and submitted a revised draft of the convention to the President for his use at the peace conference.

Under date of August 9, 1919, the Secretary of State officially submitted to the committee a copy of the proposed convention for the regulation for international air navigation prepared by the Inter-Ministerial Commission of Civil Aeronautics and requested that the National Advisory Committee for Aeronautics give this proposed convention its early consideration and furnish him any comment or suggestions or statement of views it may feel called upon to make, adding that the convention was at that time the subject of conferences between representatives of the various powers at Paris. He stated furthermore that the following governmental agencies had similarly been requested to give consideration to the proposed convention: War, Navy, Treasury, and Post Office Departments, Geological Survey, and Patent Office.

A special meeting of the executive committee of the National Advisory Committee for Aeronautics was accordingly held on August 14, 1919, at which a special subcommittee on international air navigation was appointed consisting of representatives of the Weather Bureau, the Army and Navy Air Services, the Post Office Department, the Customs Service, the Geological Survey, the Commissioner of Patents, the Manufacturers Aircraft Association, and the National Advisory Committee for Aeronautics. The functions of this subcommittee were defined as follows:

First. To consider the convention relating to international air navigation and the report of the aeronautical commission thereon rendered to the conference of peace.

Second. To discuss the contemplated reports to the Secretary of State of the various departments before official transmission to the State Department.

Third. To endeavor to coordinate as far as possible such criticisms, suggestions, or reservations as various departments may contemplate reporting separately to the Secretary of State.

Fourth. To submit a report with recommendations to the executive committee.

The special subcommittee on international air navigation, above referred to, held meetings on August 20 and 26, 1919, at which all agencies above referred to were represented with the exception of the Manufacturers Aircraft Association. The special subcommittee was a useful agency not only for considering the convention from the point of view of the National Advisory Committee for Aeronautics but also for coordinating the views of the various departments whose opinions had been requested by the Secretary of State. It submitted its report on September 12, 1919, recommending that the United States accept the convention with certain reservations, which were stated. The report of the special subcommittee was approved by the National Advisory Committee for Aeronautics and transmitted to the Secretary of State on September 15, 1919.

COMPILATION OF LAWS ON AIR NAVIGATION.

In December, 1918, the committee made a compilation of the laws and regulations governing aerial navigation in all countries, States, and cities, including the findings of committees and international organizations relating to the subject.

FEDERAL REGULATION OF AERIAL NAVIGATION.

In November, 1918, the committee made a census of the legislation enacted by the various States of the United States for the regulation of aerial navigation. With a further view to recommending legislation for the Federal regulation of aerial navigation, the committee under date of November 6, 1918, requested the Secretaries of War, Navy, and Commerce, and the Postmaster General to designate special representatives to cooperate with the committee. These representatives were appointed and a Special Interdepartmental Conference on Aerial Navigation was organized as follows:

WAR DEPARTMENT:
Col. Arthur Wood.
Col. F. R. Kenney.
NAVY DEPARTMENT:
Rear Admiral W. R. Shoemaker.
Commander J. H. Towers.
POST OFFICE DEPARTMENT:
Mr. Otto Praeger.
DEPARTMENT OF COMMERCE:
Dr. S. W. Stratton.
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS:
Dr. Charles D. Walcott.
Dr. Joseph S. Ames.

The interdepartmental conference elected Dr. Walcott chairman and appointed a subcommittee on aerial legislation, with Admiral Shoemaker as chairman, to draft the proposed legislation. This subcommittee first recommended legislation authorizing the appointment of a joint board consisting of the Secretaries of War, Navy, Commerce, and Treasury, and the Postmaster General to regulate aerial navigation in the United States, but this recommendation was not approved. The transfer of the military and naval members of the interdepartmental conference on aerial legislation to duty outside of Washington terminated its activities.

The executive committee of the National Advisory Committee for Aeronautics gave further consideration to the question and under date of February 21, 1919, transmitted to the President a draft of proposed legislation placing the regulation of aerial navigation under the Department of Commerce together with a statement of the reasons therefor. The committee first secured the approval of the Secretaries of War, Navy, and Commerce to this proposed legislation, and, thus indorsed, it was approved by the President on February 25, 1919, and transmitted to Congress through the Secretary of the Treasury on February 26, 1919. It failed to pass at that session of Congress, however, due to the great crush of business at the end of the session. The Joint Army and Navy Board on Aeronautics, having authority only for the duration of the war, has continued temporarily to issue licenses for aviators pending the enactment of Federal legislation on this subject.

CIVIL AERIAL TRANSPORT.

The committee believes that the development of civil aerial transport on a commercial basis is assured. The greatest need at the present time is the proper location and maintenance of suitable landing fields in every city and town. These landing fields should be established and maintained by the municipalities as part of park systems. The Government should cooperate at the beginning by assisting in laying out the fields according to approved specifications and by the erection of at least one airplane hangar on each field. The fields should be made available for use alike by Government and private aviators. The initiative in this matter properly rests with the people, under our principles of Government, but it is deemed appropriate at this time to invite attention to the fact that the Governments of Great Britain and of France have offered comparatively large sums of money as prizes for certain developments in aeronautics and also as subsidies for the establishment and maintenance of com-

mercial air routes. Commercial aeronautics will be very slow indeed to get started in the United States in the absence of material encouragement and help from the Government. At the present time there is no governmental agency duly authorized to expend funds in aiding the development of commercial aviation.

Dr. W. F. Durand, a member of the Advisory Committee, prepared a comprehensive statement of the need, the opportunity, and the difficulties of establishing commercial aviation in this country, which was issued by the committee in August, 1919.

AIRCRAFT STANDARDS.

The International Aircraft Standards Commission established during the war adopted a program calling for the permanent participation of various nations in such a commission with a view to the establishment and maintenance of standard terms amd practices for aeronautics. In June, 1919, the committee recommended to Congress that it be authorized, along with other Government departments, to advise in the selection of representatives to attend such a conference abroad if American participation were approved by Congress. In the absence of such approval by Congress, the Committee on Aerodynamics of the National Advisory Committee for Aeronautics has undertaken the establishment of certain aeronautical standards in this country with the cooperation of the military and naval air services, the Bureau of Standards, and other Government agencies concerned.

NOMENCLATURE FOR AERONAUTICS.

During the past year the committee has continued its work on the standardization of English nomenclature for aeronautics. It is at present engaged in an extensive revision of its last report on nomenclature (No. 25) published in the fourth annual report. It is proposed to make the nomenclature more comprehensive, to illustrate definitions where necessary or advisable, and to include aerodynamic symbols. After agreement has been reached among the various interested agencies in America, the committee will undertake to secure uniformity with Great Britain in the use of technical terms and symbols.

BIBLIOGRAPHY OF AERONAUTICS.

The committee has continued the bibliography of aeronautics during the past year. The publications on this subject are printed and issued apart from the annual reports. The first work on this subject was prepared by Mr. Paul Brockett of the Smithsonian Institution and included the period up to 1910. The committee has prepared a bibliography of aeronautics from 1910 to 1916 in two volumes, and a bibliography for the years 1917 and 1918 has been prepared in one volume. It is the present policy of the committee to issue a current bibliography annually in the future.

AERIAL PHOTOGRAPHY.

On March 7, 1919, a Special Subcommittee on Aerial Photographic Surveying and Mapping was appointed consisting of Dr. Joseph S. Ames, Dr. John R. Freeman, Dr. John F Hayford, and Dr. Charles F. Marvin, to consider ways and means of coordinating the activities and methods of the various governmental agencies interested in the application of aerial photography to surveying and mapping. On invitation of the Executive Committee, based on recommendation of this special subcommittee, representatives of the following governmental agencies met with the Subcommittee on Aerial Photographic Surveying and Mapping on April 23, 1919: The Air Service of the Army; Corps of Engineers, United States Army; Naval Air Service; Geological Survey; Coast and Geodetic Survey; Post Office Department; Bureau of Standards.

The National Advisory Committee for Aeronautics suggested that consideration be given by the representatives of the various governmental agencies interested to the phases of aerial photography and mapping which the various agencies were best qualified and equipped to handle, in order that the work of each may be made to fit, where practicable, into that of the others, and made other suggestions with a view to organizing the aerial photographic work of the Government in a manner calculated to secure the best results.

The committee on aerial photographic surveying and mapping, as a result of its conference with representatives of other departments, recommended the formation of an interdepartmental committee on aerial surveying. This recommendation was approved by the Executive Committee and an interdepartmental committee on aerial surveying was formed and the committee on aerial photographic surveying and mapping was discharged.

INTERDEPARTMENTAL COMMITTEE ON AERIAL SURVEYING.

In accordance with recommendation of the committee on aerial photographic surveying and mapping of the National Advisory Committee for Aeronautics, the executive committee of the National Advisory Committee for Aeronautics invited the heads of various Government departments to designate representatives of the various Government bureaus and agencies interested in aerial photography for mapping purposes to serve as members of an interdepartmental committee on aerial surveying. In accordance therewith, an interdepartmental committee on aerial surveying was formed, consisting of representatives of various Government organizations as follows:

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS:
Dr. Charles D. Walcott.
Dr. John F. Hayford.
WAR DEPARTMENT:
Air Service of the Army—
Lieut. Col. John S. Sullivan.
Capt. H. E. Ives.
Corps of Engineers—
Col. E. E. Winslow.
Col. E. H. Marks.
NAVY DEPARTMENT:
Aviation Section—
Lieut. W. L. Richardson.
Hydrographic Office—
Commander E. H. Tillman.
DEPARTMENT OF THE INTERIOR:
Geological Survey—
Dr. George Otis Smith.
Mr. R. B. Marshall.
General Land Office—
Mr. I. P. Berthrong.
Mr. Arthur D. Kidder.
Reclamation Service—
Mr. C. A. Bissell.
Mr. E. C. Bebb.
DEPARTMENT OF AGRICULTURE:
Forest Service—
Mr. A. F. Potter.
Mr. C. A. Kölb.
Soil Survey—
Dr. Curtis Fletcher Marbut.
Mr. Ellsworth M. Eastwood.
Bureau of Public Roads—
Mr. V. M. Pierce.
Mr. M. O. Eldridge.
POST OFFICE DEPARTMENT:
Aerial Mail Division—
Mr. James C. Edgerton.
Topography Branch—
Mr. David M. Hildreth.
DEPARTMENT OF COMMERCE:
Coast and Geodetic Survey—
Col. E. Lester Jones.
Mr. William Bowie.
Burea of Standards—
Mr. W. F. Meggers.

The first meeting of the interdepartmental committee on aerial surveying was held on May 2, 1919, and an organization effected by the election of the following officers:

Chairman, Dr. Charles D. Walcott, of the National Advisory Committee for Aeronautics;

Vice chairman, Col. E. Lester Jones, of the Coast and Geodetic Survey;

Secretary, Lieut. Col. John S. Sullivan, of the Air Service of the Army;

Assistant secretary, Mr. John F. Victory, of the National Advisory Committee for Aeronautics.

A subcommittee on program was appointed, consisting of representatives of six services of the Government, with Dr. George Otis Smith, of the Geological Survey, as chairman. This subcommittee on program considered the needs of the various services and submitted the following report, which was adopted at a meeting of the Interdepartmental Committee on Aerial Surveying on May 16, 1919:

REPORT OF COMMITTEE ON PROGRAM, INTERDEPARTMENTAL COMMITTEE ON AERIAL SURVEYING.

Airplane photography as an aid in mapping can not be divorced from surveying. Its only use in mapping must be as an adjunct to surveys on the earth's surface. Thus, first in order of importance, is the definite adjustment of the airplane photograph to the mapping scale by ties to the horizontal control established on the ground.

In the practical procedure, the first requirement is that the photograph be taken in a horizontal position, or that it be rectified so as to bring it into the horizontal position, and thereby eliminate distortion due to tilt of the camera. The second requirement is that distortions due to relief of the earth's surface be corrected. The third requirement is that of bringing the pictures to a uniform scale. When these requirements have all been met the data are at hand for reconstructing on the map those features of the earth's surface which are to be projected on the horizontal plane.

Even with the maximum of perfection in airplane photographic technique the results for mapping purposes can not exceed in accuracy the quality of the ground control.

The present stage in the application of aerial photography to map making relates only to the representation of the horizontal elements of the map; as yet land relief can be regarded as only an obstacle to be overcome in the mapping of horizontal features. The future development of relief determination from the airplane will be chief subject for study for a properly constituted aerial photographic research laboratory, working in conjunction with experts from the various mapping bodies.

The practical program now presented includes the following:

1. The surveying agencies now authorized by law should continue their work to meet their own needs, and the interdepartmental committee on aerial surveying should act in an advisory capacity to facilitate such work.

2. The four surveying and map-publishing bureaus should continue in their respective fields, cooperating as hitherto, and together utilizing to the fullest extent possible this new instrument.

3. To secure the best results, the cooperation of the Army and Navy Air Services with each other and with the other bureaus is absolutely requisite. Cooperation is not only economical, but essential to efficiency.

4. Effective public service can not be attained in highly technical work by giving over to a new organization functions already possessed by another organization with an equally specialized personnel. Neither should the old organizations seek to invade the province of air navigation, which by all practical considerations should belong exclusively to the two air services.

5. The surveyor must be an experienced topographic engineer whether he operates from the airplane with the camera as his instrument or on the ground with the plane table. He must be trained in the study of topographic forms in order that he may plan his work after having made the necessary reconnaissance flights, that he may keep properly plotted on his record map the progress of the surveys, and particularly that he may put down the

numerous notes absolutely necessary for expeditiously and correctly assembling the pictures after they are taken. The resulting map will be a composite, and the securing of the map details either from the air or on the ground must be under the control of the engineer working under the direction of the surveying bureau.

6. Transportation in the air is a specialized problem for the accomplishment of which the surveying bureaus must look to the air services. Experience has demonstrated that correct flying for photographic surveying is probably the most difficult work required of the pilot and is only attained on his part by training and by the most careful attention to his task while in the air. In rendering this aid, the air services will cooperate in an important function of the Government, at the same time maintaining their own personnel in a high state of technical training and efficiency.

7. The present emergency in applying aerial photography to this desired use necessitates the immediate creation of a subcommittee on technical research, for the scientific investigation of instruments and methods. We recommend, therefore, the appointment of a representative but small committee, and suggest the following men for service on this committee:

Lieut. W. L. Richardson, Naval Air Service.
Capt. H. E. Ives, Army Air Service.
Maj. J. W. Bagley, Corps of Engineers and Geological Survey.
Lieut. Earl F. Church, Coast and Geodetic Survey.
(During Maj. Bagley's absence in France, Mr. F. H. Moffit, of the Geological Survey, to serve in his place.)

The immediate work of this committee should be to compare the progress made so far by the different workers and make plans for the solution of the present most pressing problems. To get the results immediately needed, we also recommend the organization of an aerial photographic research laboratory, under such auspices as may be advisable and feasible, with personnel and equipment adequate to handle the problems presented by the various bodies concerned with the utilization of aerial photography for the Government, both in peace and in war.

In accordance with subsequent action at the same meeting, an executive committee was established and also a subcommittee on technical research. Letters were addressed to the Secretaries of War and of the Navy through the National Advisory Committee for Aeronautics recommending that the existing restrictions in the military and naval regulations be removed to permit the taking of photographs from aircraft for mapping purposes by persons outside the military and naval air services.

The National Advisory Committee for Aeronautics transmitted these recommendations to the Secretaries of War and of the Navy with its recommendation that, in view of the fact that map making by the use of aerial photography is still in the experimental stage and that the equipment available for this work is in the hands of the military and naval air services, these services should cooperate with all agencies of the Government interested in the application of aerial photography to map making by the taking of such photographs as may be desired by such agencies. This recommendation was approved by the Secretary of War. The Secretary of the Navy went further in the matter and agreed to authorize the taking of such photographs by persons in the service of the various map making agencies of the Government.

No further meetings of the full interdepartmental committee on aerial surveying have been held, but its executive committee and the subcommittee on technical research have continued to function. The organization and work of the interdepartmental committee on aerial surveying have not involved the direct expenditure of public funds.

AERONAUTICAL INVENTIONS.

The committee has continued during the past year the analysis and disposition of inventions in aeronautics submitted directly to it by inventors or referred to it after preliminary consideration by the military or naval air services or other branches of the Government. The volume of this work has been greatly reduced since the armistice but the average merit of the propositions

considered has been of a higher order. Inventions submitted to the committee are given preliminary consideration in the office of the committee and if deemed worthy are referred to the proper subcommittee for detailed consideration or inspection as the case may warrant. In this procedure novel ideas of merit are brought promptly to the attention of the various services interested.

ARMY MEDICAL RESEARCH WORK ON AVIATORS.

In accordance with a War Department order in October, 1917, the following officers were directed to report to the chief surgeon of the Aviation Section, Signal Corps, for assignment to duty as members of the medical research board of the Air Service: Maj. John B. Watson, Maj. Wm. H. Wilmer, Maj. Edward G. Seibert, and Maj. Eugene R. Lewis. Dr. Yandell Henderson, professor of physiology at Yale University, was added to the board in civilian capacity and was appointed chairman.

The powers delegated to the board were as follows:

1. This board shall have discretionary powers to investigate all conditions which affect the efficiency of pilots;
2. To institute and carry out at flying schools or elsewhere such experiments and tests as will determine the ability of pilots to fly in high altitudes;
3. To carry out experiments and tests at flying schools or elsewhere to provide suitable apparatus for the supply of oxygen to pilots at high altitudes;
4. To act as a standing medical board for the instruction of all matters relating to the physical fitness of pilots.

In accordance with this authority the board worked at first in association with the Bureau of Mines, to whom a great deal of credit is due for assistance and cooperation in the early days of the war. The board later became independent.

In order to work out these problems the Medical Research Laboratory was established at Mineola, N. Y. The laboratory was divided into the following departments: Physiology, cardiovascular, psychology, otology, ophthalmology, neurology and psychiatry. Later a department of physics and engineering was added.

The immediate military problem of classification was preceded by certain necessary research on which to establish the basis of such classification. Specialists from all parts of the country were called in to assist in the work of the various departments. Special apparatus had to be constructed for a great deal of the work. In spite of this, it was not long before a routine test for the classification of aviators was developed, which will be described later, and research on numerous other points was taken up. In order to facilitate the classification of aviators, twenty branch laboratories were planned at the various flying schools and ground schools. The personnel for their operation was trained at the central laboratory, and ten of the branch laboratories were in active operation before the armistice was signed. When flight surgeons were needed they received their training at the central laboratory, as did the physical directors of the Air Service. A laboratory unit under the command of Col. William H. Wilmer was organized from the personnel of the main laboratory and went overseas for duty with the expeditionary forces. The research work has continued since the armistice.

A brief outline of the work accomplished at the laboratory is as follows: First of all the physiology of altitude was carefully studied. A great deal of work had been done with this in previous years on Monte Rosa in Europe, and Pike's Peak in the United States. Most of the changes that result on mountains are the result of residence at that altitude for a considerable period of time. An aviator does not remain at high altitude any length of time, consequently permanent adaption to physiological changes does not occur. The effects of aviation were studied in actual flying, and by simulating aviation with the use of a low pressure tank and a rebreathing machine.

The low pressure tank consists of a steel tank controlled by an exhaust apparatus by which the atmospheric pressure and the oxygen can be reduced at will, together with provision for a fresh supply of air, so that any altitude may be simulated from sea level up to 36,000 feet.

A description of the rebreathing machine is quoted from "The Air Service Medical":

> The base of the machine is a steel tank of 60 or 80 liters capacity, according to the type. Air is inspired from the tank through the pipe at the left, and is expired back into the tank through the pipe and absorbing cartridge at the

right. The valves keep the air stream flowing always in the proper direction. In order to maintain the contained air at approximately atmospheric pressure and to allow for changes in volume, a wet spirometer, carefully counterbalanced, is mounted on the tank and communicated freely with its interior through the vertical pipe. A stylus attached to the counterweight records the movements of the spirometer upon the smoked drum of the kymograph. Water is admitted to the tank through a valve to replace the volume of the used oxygen and also to flush out the tank after an experiment. The water is drained away to the sewer by means of a valve. A valve affords a free opening to the atmosphere for flushing the tank of the rebreathed air.

It was soon shown that the factor of atmospheric pressure was of secondary importance. By means of this rebreathing apparatus the physiology of low oxygen in aviation was studied.

Comparisons of the rebreathing tests with the dilution test; the effect on the breathing when under the action of progressive decrease in oxygen; the effect of a decreasing oxygen supply on the circulation; the effect of arterial, venous, and capillary pressure; the question of the vasometer tone and endurance of low oxygen; the effects on the pulse rate and the haemoglobin; alveolar air pressures; carbon dioxide capacity of the blood; and the relative value of the compensatory factors were studied. The effects of low oxygen on circulatory physiology; the relation of the vasomotor control of the heart; nervous factors in vasomotor control; the question of compensation; heart strain; the arrhythmias, and the effect on valvular disease and athletic hearts were also studied. These points covered the physiological side.

The function of psychology in respect to the aviator is to study his adaptability to the work required of him. Physiology tells us how the body reacts to low oxygen, and it was the duty of the psychology department to determine how the mind acts under low oxygen. The psychological rating of aviators for altitude limits; the development of an apparatus for a standard test; the investigation of the psychological qualifications of the flier; and experiments on psychological reaction under low oxygen tension are some of the points taken up by the psychology department.

As a result an apparatus was developed for the standard test. A description of this apparatus is quoted from "The Air Service Medical:"

(*a*) The apparatus mounted on the table forms three separate units: (1) A series of 14 stimulus lamps (2 candle power) arranged in two rows of seven each, with two similarly arranged rows of contact buttons, each surrounded by a washer; a green check lamp and a red error lamp, and a stylus with a hard-rubber handle and metal tip. These parts of the unit are so wired electrically that when a stimulus lamp lights the corresponding contact button is "alive," and if touched with the metal tip of the stylus causes the check lamp to light. If the washer surrounding any of the buttons is touched with the stylus at any time the error lamp lights. (2) Two ammeters mounted on a metal arm above the table top are connected in series with two rheostats, one on the upper side of the table top at the edge nearer the reactor, the other underneath at the edge nearer the psychologist. A change in the resistance made by the psychologist at his rheostat, causing a change in the ammeter reading, may be compensated for by a change in the reactor's rheostat, by which the original ammeter reading may be restored. (3) A small electric motor mounted on the upper side of the table top is connected in series with a third rheostat underneath the table. A 2-way lever switch mounted underneath the table at the edge next to the psychologist and a rocking pedal 2-way switch on the floor under the table are connected with the rheostat by a 3-wire system, so that a part of the resistance of the rheostat can be cut out (thus increasing the speed of the motor) by either switch and again cut in (thus restoring the lower motor speed) by either switch.

The rebreathing examination is made following a general physical examination and the taking of a careful medical history. A description of the rebreathing examination is quoted from "The Air Service Medical:"

The evidence is sufficient that this test is a perfectly reliable index of tolerance to low atmospheric pressure, and the low-pressure chamber has been used not as a routine method of examination, but only as means of checking up the results of the other test and for scientific purposes.

The rebreathing machine is so adjusted that the average run will be between 25 and 30 minutes. During the run the subject does the psychological work, as described later, and is carefully observed by the psychologist to determine the earliest effects on attention and motor coordination, as well as the time of appearance of more marked effects and of total breakdown.

Every three minutes the capacity of the external and internal ocular muscles is retested during the run. (This has since been eliminated from the test.) During the whole test the pulse and blood pressure, systolic and diastolic, are measured every one or two minutes. The clinician keeps close watch of these figures and makes frequent examinations of the heart. The respiration is recorded throughout the test on a kymograph.

The test ends when the psychologist has determined that the subject has reached the point of complete inefficiency, or when the clinician finds that the condition of the circulation makes prolongation of the test undesirable. At the close of the run the air remaining in the apparatus is analyzed to determine the oxygen percentage reached, which can be translated roughly into terms of altitude. A few subjects have exhausted the oxygen to 6 per cent or a little lower. Seven per cent is a frequent figure, while poor subjects either become inefficient or faint at considerably higher percentages.

The results of the test are summarized in a plot of which the abscissa line represents minutes of time and the ordinates are per cent of oxygen, and figures representing pulse, blood pressure, volume of respiration, millimeters of near point of convergence, etc. The appearance of different degrees of inefficiency by the psychological tests is indicated by symbols placed at the proper time on the abscissa line. It is assumed (with reasonable correctness) that a straight line connecting the oxygen per cent at beginning and end will represent the per cent at all intervening times. The basis of judgment on the success of the subject is the oxygen percentage at which various phenomena occur, and this is reckoned from the height of the oxygen line at the time in question.

The decision as to rating the subject is made by consensus of opinion on the basis of the ratings made by each separate department and is ordinarily the lowest rating assigned by any one of them. No man is passed in class A who has any considerable disqualification from any point of view. For example, a deficiency in vision, whether ordinarily present or only developing as the result of the test, would disqualify for combat work, no matter how well the candidate performs otherwise.

Aside from ocular deficiencies or general physical conditions of a distinctly abnormal nature, the rating of a subject depends on the answer to two questions: How well does he adapt himself to the unusual environment—i. e., how well does he preserve his efficiency at altitude (as expressed by the psychological tests); and, second, at the expense of how much strain on his circulatory system does he do it? Many subjects will compensate admirably, preserving their efficiency to a very high altitude, but only by means of a very high blood pressure, high pulse, or violent vasomotor reactions such as would lead us to expect that this man would wear out quickly in service or perhaps actually have a circulatory collapse in the air and faint.

The psychological test referred to is also quoted from "The Air Service Medical."

As soon as rebreathing commences, the reactor begins to respond to the three sets of stimuli as presented by the apparatus under the manipulation of the psychologist. During the first three minutes of the test the psychologist shall coach the reactor, if necessary, and estimate his comprehension composure (freedom from excitement or nervousness) entering theses on the record sheet then or later as good, fair, or poor. He should also note the motor tendencies of the reactor, and if these fall in one or more of the conventional categories, this also should be entered.

In addition to these general tendencies, it is important that the psychologist take notice of the specific tendencies shown by the reactor, and if definite types of error are shown, watch during the succeeding five or six minutes for improvements in these details.

Normally, the test continues until complete inefficiency is reached, at which point the psychologist must sharply notify the responsible medical attendant in order that the reactor may at once be given air, and so prevented from undergoing the collapse which would ensue in a minute or so.

The psychologist will record the typical change in the reactor's behavior, using the symbols which are given on the "symbol sheet," so that the recording will interfere as little as possible with the observing. After the test is ended, the entries on the record sheet must be at once completed.

The ratings are divided into four classes:

Class "A" Those fit for any work.
Class "B" Those fit to fly up to 15,000 feet.
Class "C" Those fit to fly up to 10,000 feet.
Class "D" Those that are not fit to fly at all.

There has been added to the classification examination a personality study by means of which the applicant is classified with respect to aviation according to the condition of his nervous system. A great deal of work has been done on personality study by the psychiatry department, and the latter has proven to be one of the most if not the most valuable department so far as the care of the flier is concerned.

Further research work has been done by the physiology department. A new type of rebreather and other respiratory apparatus; respiratory volumes of men during short exposure to constant low oxygen tension attained by rebreathing; the changes in the content of haemoglobin and erythrocytes of the blood in man during short exposures to low oxygen; circulatory responses to low oxygen tension; alveolar air and respiratory volume at low oxygen tensions; compensatory reactions to low oxygen; and the reaction of the cardiac and other respiratory centers to changes in oxygen tension, are some of the subjects studied.

The cardiovascular department has put a great deal of study on the question of the effect of altitude on the aviator's heart, and some very interesting and rather startling discoveries have been made by research with the X ray, rebreathing machine, and low pressure tank. It has been shown that the heart does not dilate at high altitudes, as formerly thought. If has also been shown that there is a wide variance in the transverse diameter of the heart during forced inspiration and expiration. Further research is contemplated on this same subject and work is underway and projected on the electrocardiographic study of the heart under low oxygen and in the condition known as "staleness."

The psychology department has done further work on the psychological effects of the deprivation of oxygen and the psychopathology of aviation.

The ophthalmology department has worked on the subject of the strain of flying on the eye, the value of the eye in aviation, the reaction time, retinal sensitivity, effects of tobacco on the vision, testing of retinal contrast and threshold sensitivity, the development of a new apparatus for testing stereopsis, dark adaptation, the judgement of distance, the speed of accommodation, and improved tests for muscle balance. This department as the result of its work, has recommended a complete revision of the standard of examination for candidates for aviation. This will result in the adoption of a much more complete and thorough examination than has been in vogue heretofore.

The otology department worked on the subject of the effect of low oxygen on the phenomena of nystagmus and past pointing; the revision of the standards of examination on the tests of equilibrium, motionn sensing experiments in the linear upward and downward direction both in normal individuals and in deaf mutes and tabetics; observation upon motion sensing during airplane flights of the same group of subjects; and the ear in stunt flying. An abstract of literature on the anotomy and physiology of the semicircular canals has also been made. Considerable work has been done on the orientator, which is a machine consisting of the cockpit of an airplane suspended in three concentric rings, capable of all the motions of an airplane except forward motion, and is controlled by a rudder and a stick, the same as an airplane. It is devised to train cadets against the physical effects of stunt flying. In other words it accustoms a man to the rapid change in motion and position which he experiences in stunt flying and allows him to become adapted to these sensations before he ever leaves the ground. Considerable clinical work was done on the effects of syphilis on the internal ear.

The physics and engineering department has worked on the subject of aviators' goggles, and has tested out oxygen supply apparatus.

In addition to the subjects already mentioned, it is contemplated to take up the following points of research: A statistical study of the records of 5,000 aviators with reference to sources of variation in phychological rating; the statistical rating of the psychological tests of skill of aeronautical obsevers; the effects of the deprivation of oxygen on the higher processes; diagnostic value of the determination of the reaction time in tests for aviational ability for staleness; dermographia as a test for staleness; tests for retinal sensitivity; the effect of low oxygen on depth perception; the use of protective substances in the ears to diminish excessive roar of airplane motors.

The laboratory, as at present instituted, is probably more completely equipped for the study of the medical problems of aviation than any like institution in the world.

All departments have combined in revising the standard for physical examination for flying status and all departments are interested in the subject of staleness and fatigue in the aviator. This latter is one of the most important subjects in aviation medicine.

Three lines of work are carried on at the laboratory:

1. Research in medical problems of aviators.
2. Instruction of flight surgeons.
3. Examination and classification of aviators.

The flight surgeon is a production of the war and is a medical officer specially trained in the care of the flier, and one who by his work prevents accidents. The facts developed at this laboratory, and at flying fields, as well as in foreign armies, have shown the necessity for the flight surgeon. The ordinary medical officer is not prepared to take care of the flier. Medical

officers selected for this duty are given a course of intensive training for two months at the Medical Research Laboratory. This course consists of lectures, demonstrations, practical and clinical work.

THE AIR MAIL SERVICE.

On May 15, 1918, the Post Office Department inaugurated the Air Mail Transportation Service. It had previously sought and received the advice of the National Advisory Committee for Aeronautics as to routes, methods, types of planes, etc. At the suggestion of the Chief Signal Officer of the Army the service was originally conducted by the War Department in connection with its work of training aviators for the war which was then being prosecuted. The service continued under military direction until August 10, 1918, when it was taken over by the Post Office Department and operated by an entirely civilian organization.

The only equipment available at the time of the establishment of the Air Mail Service was a few *J. N.—4–H* and *R–4* Army training planes with a capacity of 200 pounds of mail. With the close of the war quite a number of *D. H.–4* planes were made available to the Post Office Department, which made it possible to increase the mail load to 400 pounds. These airplanes, however, were designed wholly for war purposes and lacked the necessary strength for daily cross-country flying with its incidental forced landings. It was necessary to modify this equipment which resulted in the development of an airplane better adapted to the requirements. These changes consisted of a greatly strengthened landing gear, fuselage enforcement, and transposition of cock-pit and cargo compartments.

While the performance of these airplanes as remodeled was generally satisfactory, it was necessary for the Post Office Department to contract for the construction of large multi-engined airplanes in order to insure reliability in performance of mail schedule trips and to provide for larger mail dispatches. Orders were placed for 14 airplanes, 6 of the Martin bomber type, 4 of the Thomas-Morse modified type, and 4 airplanes of 104-foot wing span by the L. W. F. Engineering Co.

A recent development is the transformation of a *D. H.–4* airplane into a twin-engined airplane. This airplane is equipped with two 200-horsepower Liberty-six engines, has developed a speed of 103 miles per hour, will maintain horizontal flight with one engine, and will carry 800 pounds of mail.

The service has been keenly alive to the important matter of fire protection and has equipped ts airplanes with fireproof bulkheads and liquid extinguisher systems with automatic crash release device. Improved fire protection systems are being installed in the larger airplanes now under construction.

Complete radio telegraphic communication will shortly be installed by the Air Mail Service, together with triangulation stations, which will make possible a complete dispatching system whose main function will be to locate airplanes accurately at any moment during flight. Distant controls are also being developed in order that the Department at Washington may get in direct communication with any pilot in flight by means of radio telephone. The amplifiers developed by the War and Navy Departments were made available to the Air Mail Service.

A statement of the work of the Air Mail Service would be incomplete without reference to the service performance in the air. Early advices received by the Post Office Department were that there would be great difficulty in maintaining a daily schedule of mail flights, and the opinion was held that the service would be interrupted during the winter months and perhaps at other times when conditions might be considered unpropitious. However, the rapid development of aviation generally has made it possible to establish a reliable service, as is shown by the following record: During the last fiscal year only 4.4 per cent of the scheduled trips were not attempted, and out of a total of 138,310 miles possible there were flown 128,255 miles, or a performance of 92.73 per cent. During the same period there were only 37 forced landings, due to mechanical troubles during flight.

It would seem, therefore, that the achievements of the Air Mail Service may be regarded as a substantial contribution in the practical development of commercial aviation.

METEOROLOGY IN AID OF AERONAUTICS.

As a result of the appropriation of $100,000 granted by Congress on recommendation of the Advisory Committee, for the fiscal year 1918, to be expended by the Weather Bureau under the direction of the Secretary of Agriculture, important extensions were made in the whole program of work of the Weather Bureau in the conduct of investigations of meteorological conditions in the free air.

Five stations fully equipped for making observations with kites and sounding balloons were approximately distributed over the United States, and a number of additional stations conducting observations by means of pilot balloons were also established both by the Weather Bureau and by the Signal Corps of the War Department. The data obtained from these additional observations, supplementing the surface observations at 200 stations of the Weather Bureau, led to the inauguration in December of 1918 of a regular system of forecasts of free air conditions which were supplied daily to the Signal Corps, the Post Office Department, the Director of the Air Service, and others who desired them. In the beginning the regions covered were principally the mail routes between Washington, Philadelphia, and New York, and later on extended to the mail routes between New York and Chicago. Special information was furnished the Army as occasions might require.

The appropriations for this activity have been continued in the regular appropriations of the Weather Bureau, and in more recent times have been supplemented by some cooperative reports from base stations maintained by the Navy at coastal points. The forecasting work has been, moreover, more fully systematized and extended, the area of the United States being divided into 13 forecast zones, for which forecasts are supplied to the Director of the Air Service for distribution to those localities where flight is in progress.

A considerable amount of free air data has been compiled, tabulated, and published in the Supplements of the Monthly Weather Review, and several important articles discussing average free air conditions have also been published in the Monthly Weather Review itself to make this information more generally available to aeronautical and military interests.

In addition to the foregoing systematic work of the Bureau, special arrangements of cooperation with the Army and Navy have been made for the purpose of supplying the fullest possible meteorological information in connection; first, with the trans-Atlantic flight of the naval airplanes; second, in connection with the visit of the British dirigible, *R-34;* and, finally, in connection with the transcontinental reliability tests of the Army Air Service.

It is believed the service rendered by the aerological and forecasting work of the bureau in connection with aeronautics has been of very great value and has elicited the cordial commendation of the Secretary of the Navy. Plans are under way for the considerable extension of this line of activity, and the estimates of the Weather Bureau contain an increase of $200,000, which, if secured, will permit of the establishment of a considerable number of additional pilot balloon and kite stations in the regions of the far West.

With the passing of war conditions, moreover, balloon material becomes available for so-called sounding balloon observations, which must be made in order to carry the observations to higher portions of the atmosphere than can be reached by either kites, pilot balloons, or air craft of any character.

C. F. Marvin.

SPECIAL AERODYNAMIC INVESTIGATIONS.

In the summer of 1919 the executive committee approved a program of scientific work to be carried out at McCook Field, Dayton, Ohio, under the supervision of its aerodynamical expert, Dr. George de Bothezat. This work involved: First, the theoretical analysis of the full performance of an airplane in steady flight; second, the development of new instruments and methods in order to measure in a single test flight the full performance characteristics of an airplane; third, the analysis of the full performance record of an airplane and deductions therefrom as to how the efficiency of an airplane can be increased by minor changes; fourth, the making of such minor changes in a given type of airplane to be followed by a second full per-

formance test; fifth, the checking of the results against the original theory and the necessary modifications of the theory to permit in the future the determination of all the performance characteristics of an airplane in steady flight by mathematical calculation.

Dr. de Bothezat has been stationed at Dayton since August, 1919, and a small staff has been selected from members of the engineering division of the Air Service and assigned by the commanding officer at McCook Field to work with him in the prosecution of this work. The present commanding officer at McCook Field, Col. Thurman H. Bane, is also a member of the National Advisory Committee for Aeronautics. This work has been successfully inaugurated with the hearty cooperation of the officials and civilian engineers of the Air Service.

ACTIVITIES OF THE TECHNICAL SUBCOMMITTEES.

The technical subcommittees have been consolidated into three main committees, namely, aerodynamics, power plants, and materials for aircraft. These committees are so organized as to make possible the effective coordination of research and experimental work in aeronautics among the various agencies, as the chairman of each committee is a member of the Advisory Committee and the other members represent the Advisory Committee, the military and naval air services, the Bureau of Standards, and the aeronautic industry. The subcommittees consider and recommend the problems to be attacked, where their solution can best be undertaken, and the methods to be employed. The military and naval air services leave the study of problems of a more scientific and fundamental character to the Advisory Committee and the investigations undertaken by the Advisory Committee are carried out under the cognizance of the various subcommittees. Problems that can better be handled by the Bureau of Standards or the military or naval air services are referred to those agencies for investigation. Reports of the three main technical committees for the past year follow:

REPORT OF COMMITTEE ON AERODYNAMICS.

The committee on aerodynamics is a consolidation, made in April, 1919, of the three committees on aircraft design, navigation of aircraft and aeronautic instruments, and free flight tests.

The committee on aerodynamics recommended that in the part of the work at Langley Field within its domain the emphasis should be placed mainly on—

(*a*) Studies, in the laboratories, of propellers from the aerodynamic point of view;

(*b*) Studies, in the laboratories, of the flow of air around parts of airplanes and airships, separately or assembled, and of the forces brought to bear on those parts by the air;

(*c*) Free flight tests on full-sized machines; and

(*d*) The development of instruments, equipment, and methods for making such studies and tests.

This policy has been followed during the year.

The work at Langley Field under these four heads, carried on under the general direction of Edward P. Warner, has been largely one of development and design, although some research work complete in itself has been carried on. The wind tunnel has been under construction throughout most of the year and is now nearing completion, and a number of experiments on model tunnels have been made to determine the best form to adopt for the 5-foot tunnel now under construction. The balance for this tunnel has also been designed and constructed at Langley Field, and is ready for use. As an accessory to the design of the balance a theoretical investigation of the errors to which such balances are subject and the considerations governing their design has been made, and is published as a technical appendix to this report. The most important experimental work complete in itself has dealt with free flight tests, researches having been conducted throughout the summer on two airplanes furnished by the Air Service. These researches have dealt chiefly with the determination of the lift and drag coefficients and with the balance of the airplanes, thus giving data for purposes of comparison with those obtained in model tests. Several minor investigations on the performance of airplanes and on

stresses in the airplane have also been undertaken, and two of them are published as appendixes to this report.

The development of autographic recording instruments for free flight tests has continued at the Bureau of Standards under the general direction of John F. Hayford and Lyman J. Briggs for the committee. Of the six new instruments designed five are now complete, namely, the air-speed meter, the angle-of-attack meter, the recording tachometer, the torque meter, and the thrust meter. The first three named have passed through extensive laboratory tests and calibrations, and are substantially ready for use in the air. The torque meter and thrust meter must be subjected to extensive laboratory tests and possible modifications before they will be ready for use. The stable zenith instrument, to be used for recording continuously the angle between the wing chord and the horizontal, has been redesigned as a result of considerable experience with this type of instrument. The redesigned instrument is being built and is nearly complete.

Special investigations have been made and are still in progress at the Bureau of Standards, under the recommendation of the committee, on the Parker variable camber wing for airplanes. This is a promising line of attack of the problem of reducing the landing speeds of an airplane without reducing its flying speed. Incidentally some valuable information is being secured in regard to the possibility of using a streamline wing and the ordinary type in a biplane combination.

Researches on airplane propellers are being continued at Stanford University under the general direction of Prof. W. F. Durand.

The Bureau of Standards has undertaken four investigations for the aerodynamics committee:

1. Development of open scale altimeter.
2. Diaphragms and elastic fatigue.
3. Altitude correction for air speed indicators.
4. General report on aeronautic instruments.

The first three of these are definite experimental problems while the fourth consists not only of a summary of recent experimental investigations of instruments carried out in cooperation with the committee at the Bureau of Standards, but will go further and embrace a general survey of the state of this subject at the close of the war both in the United States and abroad.

1. The work on the open scale altimeter has progressed to a point where a working model of the essential parts of the altimeter, exclusive of the indicating mechanism, has been assembled and tested. By proper theoretical design of the spring and diaphragm elements an instrument has been made whose performance depends on the material of the steel spring almost entirely and only to a slight degree on the material of the diaphragm. It has been possible to secure steel nearly free from elastic fatigue effects, although such is not the case with the alloys used for the thin flexible diaphragm. As a result this instrument has been shown by test to have less than one-third of the fatigue effects (i. e., discrepancy between increasing and decreasing readings) permitted by the Bureau of Standards specifications for altimeters. The object of this work, which will be continued until completed, is to provide a precision altimeter suitable for altitude determination in aircraft performance tests.

2. Thin metallic diaphragms, usually corrugated for flexibility, form a necessary element in a great variety of engineering instruments, particularly in aneroid barometers for altitude measurement, in air-speed indicators, certain forms of statoscopes and rate-of-climb indicators, balloon manometers, and aviator's oxygen control apparatus. Such diaphragms are never perfectly elastic but show what are known as fatigue effects, failing to recover instantly from the deformations undergone in the normal operation of the instrument; hence, the importance of experiments to select the most promising alloys, to determine the most effective thermal and mechanical treatment in the process of manufacture, and to establish the most efficient geometrical design for the diaphragms when used either singly or in combinations. Up to the present this investigation has resulted in the development of measuring applicances for detecting the small changes in question by micrometric methods, in the preparation and use of suitable shop

equipment for spinning sample diaphragms at the bureau in considerable numbers, in a preliminary study of a variety of alloys to select those which warrant more detailed study, and in a special study of mechanical seasoning processes. This last phase of the work has led to the conclusion that diaphragms can be seasoned mechanically; that is, artificially aged and thus brought into a permanent state where they will repeat their performance in successive tests under the same conditions. This is done by repeated deformation of suitable amount several thousand times, and is done automatically by a mechanism designed for the purpose. Some such seasoning process appears to be a necessary preliminary to the comparative measurement of the effects of different processes of heat treatment, different compositions of the alloy, and different mechanical design. The seasoning process, it will be understood, is not intended to eliminate elastic fatigue, although it does always reduce it somewhat. The object of the seasoning is to secure definite and uniform results, so that those factors which will diminish the fatigue can be analyzed quantitatively.

3. It has hitherto been taken for granted that Venturi tubes, when used for air-speed indicators, will follow a familiar law which states that the suction produced is directly proportional to the density of the air and to the square of the speed.

The object of this investigation is to determine by direct experiment whether this law does apply to Venturi tubes or whether, on the contrary, the compressibility and viscosity of the atmosphere may cause some effects which will complicate the correction of these instrument for different altitudes. The experiments are conducted in a so-called vacuum wind tunnel (that is, a very small air-tight wind tunnel in which reduced pressures corresponding to high altitudes may be secured). The conclusion has been reached that the instruments examined are free from the effect of compressibility but not entirely free from the effect of viscosity. These experiments are to be completed and brought to a conclusion which can be expressed numerically for the purpose of correcting such instruments when used in aircraft performance tests.

4. The general report on aeronautic instruments presents the results of investigations made during the war by the Bureau of Standards to determine the characteristic sources of error of the various types of instruments. Tachometers, for example, for measuring the revolutions per minute of the propeller shaft are built in a variety of different types, operating on diverse physical principles. There are the chronometric, centrifugal, magnetic, electric, air viscosity, air-pump, and liquid types, each of which has its own characteristic sources of error. Aside from the ordinary errors met in engineering instruments, such as incorrect calibration, parallax, looseness of friction in the mechanism, elastic hysteresis, and secular changes, those used on aircraft may be further influenced by the physical conditions peculiar to aviation, viz, (1) extreme drop of pressure, (2) extreme change of temperature, (3) vibration, (4) acceleration or inclination. Besides the above results this report, which is nearly completed, gives a description of the instruments collected by the Bureau of Standards in cooperation with this committee during the war, including those of British, French, Italian, Russian, Danish, and German construction.

In the light of that report it will be evident that the objects toward which instrument development work should chiefly be directed in the immediate future may be summarized as follows:

1. Open scale instruments for performance testing of aircraft. These need not necessarily be so compact, light, or rugged as service instruments, and hence offer freedom for such design as will insure the highest accuracy.

2. Instruments for long distance navigation, including an absolute or ground speed indicator, and such a form of gyroscopic stabilizer as may be needed for mounting the instruments.

3. Instruments to guide the pilot in flying through fog, such as more reliable gyro turn indicators and compasses.

4. Better materials for springs and diaphragms and a more systematic determination of the thermal and elastic constants of the materials.

The Bureau of Standards has developed (primarily for the Air Mail Service) a field-marking radio device which enables a pilot to steer directly to the center of his landing field, although it may be obscured by clouds, rain, snow, of fog. This apparatus utilizes the same transmitting equipment for the ordinary radio direction finding signals and for the landing signals. The landing signals are projected vertically as an electromagnetic cone of great intensity, which can be heard satisfactorily at an altitude of three to four thousand feet. The device enables the pilot to first find the approximate vicinity of a landing field and then fly directly to its center, thus making a safe landing in a fog or in the dark. As elevated aerial systems are manifestly dangerous to air navigation, the Air Mail Service experimented extensively in radio transmission with antennas only 20 feet in height, highly directional, and admitting of sharp tuning. The installation of high-powered stations in the vicinity of flying fields is therefore made possible. Efforts are being made to provide and perfect a practical visual signal to take the place of the present audible signal requiring an audibility of 10,000 to overcome engine ignition interference noises. Such a signal will greatly enlarge the field of operation, A new type of gyroscopic nonmagnetic compass, intended to overcome the unreliability of the magnetic compass caused by vibrations and other disturbing influences of an airplane in motion, is now being developed by the Air Mail Service. This compass is now in a usable form for operation on land or sea, and only requires such changes as will adapt it to use on airplanes. It consists essentially of a solid metal ball floating on a film of compressed air and rotating coordinately in fixed relation to the earth's rotation.

REPORT OF COMMITTEE ON POWER PLANTS FOR AIRCRAFT.

During the year ended September 30, 1919, the activities of the subcommittee on power plants for aircraft have consisted in the support and general supervision of researches on a number of power plant problems of importance in aeronautics and in the preparation of a considerable number of reports setting forth the results of the researches.

The committee has maintained close relations with the several other agencies engaged in aeronautic research and development, including the Army, the Navy, the Bureau of Standards, the Bureau of Mines, and the several manufacturers engaged in production of power plants and their accessories for aircraft.

Dynamometer laboratory equipment is being installed in a temporary building on the grounds of the National Advisory Committee for Aeronautics at Langley Field, Va., to be operated in conjunction with other laboratory facilities of the committee at that point. The plans call for a series of four electric dynamometers of the following size: 300 to 400 horsepower, 200 to 300 horsepower, 45 to 75 horsepower, and 1.5 to 5 horsepower. All are equipped with sufficient auxiliary apparatus to permit securing the data necessitated by the researches scheduled for the attention of this laboratory. The purchase of the 200 to 300 horsepower dynamometer will probably be consummated shortly and the machine used temporarily as a generator to tide over the period of power shortage in both the dynamometer laboratory and the wind tunnel.

The following classification of the problems relating to aeronautic power plants may serve as a basis for an outline of the committee's work for the year:

I. Complete aeronautic power plants units.
II. Component parts of aeronautic power plants units.
    1. Heat and pressure cycles.
    2. Charging systems.
    3. Valve gears.
    4. Ignition systems.
    5. Cooling systems.
    6. Lubrication systems.
    7. Exhaust systems.
III. Fuels.
IV. Lubricants.

I. Complete Aeronautic Power Plants Units.

The study of general performance of aircraft engines by the committee has been confined to research in the Altitude Laboratory at the Bureau of Standards. The work undertaken here has included performance tests of a number of Liberty "12," Hispano "180," and Hispano "300" horsepower engines. Tests have also been made in this laboratory of one Liberty engine and one Hispano-Suiza 300-horsepower engine in cooperation between the Bureau of Standards and the air service engineering department at McCook Field. The engines were first tested at McCook Field and their performance analyzed at ground level, then they were sent to the Bureau of Standards for a complete study of their performance at altitudes, after which the same engines were mounted in planes at McCook Field, to assist in the study of plane performance in flight.

The collected data from previous tests made in the altitude chamber have been utilized for the preparation of several reports which appear in the preceding volume. Further analysis of these results is in progress and will be continued.

II. (1) Heat and Pressure Cycles.

The general research regarding heat and pressure cycles in engine operation may be divided into several parts: (*a*) The research for the determination of the rates of flame propagation in engine cylinders being carried out at the Bureau of Standards and mentioned in the last annual report has been continued and a considerable amount of valuable data collected. The results show that the propagation of flame in cylinders under normal conditions is much lower than has often been assumed. This rate plays an important part in the performance of an engine. A very comprehensive series of measurements is in progress which, when completed, will undoubtedly assist in clearing up many existing uncertainties as to the differences in the behavior of different fuels in engines. (*b*) In parallel with the above the development of high-speed gas engine indicators has been continued, and in addition to the optical indicator mentioned in the last volume there has been developed at the Bureau of Standards a new type of balance pressure indicator which gives results in many respects far superior to anything of the kind obtained previously. This indicator is being applied to the accurate recording of not only compression and explosion pressures but of intake manifold, exhaust manifold, and cylinder intake and exhaust pressures with a very high degree of accuracy. It is adapted for use in the "altitude" chamber where the engines are inaccessible during operation and is being applied to the study of cylinder pressures under these conditions. The so-called "integrating" indicator in various forms is receiving attention and one will be developed at the Langley Field laboratory.

II. (2) Charging Systems.

(*a*) Much experimental work has been in progress on the subject of supercharging of engines for high altitude flight and several lines of attack are being followed by different interests both in America and abroad. The careful study of this subject undertaken by the committee last year led to the decision that one promising line of attack was not being followed out elsewhere and it was decided to push forward work along this line.

The committee has had constructed an experimental supercharging blower of the positive (Root) type designed by one of its members and suitable for application to the Liberty "12" engine. This apparatus will be given preliminary tests at the Langley Field laboratory, after which it will be mounted on an engine and subjected to performance tests at that laboratory and probably also in the "altitude chamber" at the Bureau of Standards. Successful development to this point will be followed by tests in flight either at Langley Field or at McCook Field.

(*b*) A preliminary study of the effects of temperature on engine performance has been completed showing that this problem is an extremely complex one and will require a large amount of additional research, which is provided for during the coming year.

(*c*) The study of means for producing proper automatic compensation for altitude in aircraft carburetion has included experimental analysis, by means of the carburetor test plant installed at the Bureau of Standards, of three distinct types of altitude compensations, the performance of six different designs of carburetors at altitudes, a careful study of a number of

mechanisms operated by air pressure, study of the fuel jets in several types of carburetors, and the effects of air temperature on the metering characteristics of these fuel jets. The main results have been incorporated in reports which appear in the preceding volume.

(*d*) A preliminary study has been made to determine the effects of the pulsating flow which normally occurs in carburetors, on the behavior of carburetors and of the various means of compensation for altitude. The results obtained to date serve only as an indication of effects which may prove important when further investigated, which the committee plans to do.

(*e*) No work has been done the past year on flow through poppet valves, but the subject will be resumed at Langley Field the coming year.

II. (3) Valve Gears.

No work has been done specifically under this head.

II. (4) Ignition Systems.

(*a*) The study of spark plugs and ignition systems has been continued actively at the Bureau of Standards under the general supervision of the committee. The new spark plug porcelain developed at the bureau last year found wide application in the industry. A large number of different types of spark plugs have been carefully tested. The characteristics of several magnetos and other ignition devices have been studied.

Comprehensive reports have been prepared covering the researches in ignition, as this investigation has now reached a point where it may be considered practically complete as regards the characteristics of spark plugs and magnetos. There remains to be completed the development of means for using auxiliary spark gaps to overcome fouling of spark plugs. Some work on this subject has been in progress most of the year, but considerable remains to be done.

The Air Mail Service has supported the development of a glass and mica spark plug which is giving long life and freedom from fouling. Another quite different type is showing about equal life, indicating that the spark-plug problem in commercial flying is solvable in more than one way. Ignition reliability in this service is further increased by the addition of a reserve storage battery.

(*b*) A research undertaken to determine the causes of deterioration in high-tension ignition wiring has been completed. The formation of ozone due to the high voltage is the immediate cause of deterioration and certain materials are found which resist this action.

(*c*) A satisfactory determination of the effects of spark intensity on rate of inflammation of the charge and on the power of the engine is greatly needed. Much has been done on this problem elsewhere, but as yet this committee has not been able to undertake a comprehensive series of tests.

II. (5) Cooling Systems.

(*a*) Testing of specimens of radiator-core construction at the Bureau of Standards has been substantially completed, and during this year the results of all previous work on these specimens have been analyzed and incorporated in a series of reports which appear in this and the Fourth Annual Report.

(*b*) Researches are in progress or completed to determine the pressure and temperature distribution within the cells of typical radiators and the effect of the nature of the surface exposed to the air on these relations. The results show that the efficiency of a radiator used at high air speeds is always decreased by roughness of the surfaces or by irregular structures which produce turbulence.

(*c*) An experimental and a mathematical analysis of the problem of air cooling of cylinders have been undertaken. Among other things it has been found possible to calculate the dimensions of cooling flanges to be used under almost any condition, such that they will give the maximum of cooling capacity with a minimum of metal.

II. (6) Lubrication Systems.

No work has been done under this specific head.

II. (7) Exhaust Systems.

No active work has been done during the year on the subject of muffling systems, although the subject is considered of importance and will be advanced during the coming year as fast as possible.

III. Fuels.

(*a*) A special research was undertaken in 1917 by private parties under the auspices of the committee to determine the practicability of a proposed method of producing high-grade aviation gasoline without the usual chemical treatment. This work, which was carried out at Charleston, W. Va., was completed during the year and the results reported.

(*b*) Tests of some special airplane fuels have been made at the Bureau of Standards in cooperation with the committee to determine the suitability of these fuels for aircraft or military use. Among these, one, an alcohol-gasoline-benzol mixture tested at the request of the Navy Department, gives interesting results in that it appears to reduce decidedly the tendency of the engine to "knock" even at extremely high pressures. A mixture of benzol and cyclohexane, prepared by the Bureau of Mines, was subjected to a very complete series of tests and shows the same properties as the foregoing as regards tendency to "knock," but shows a somewhat higher rate of fuel consumption.

A blended fuel (composed of gasoline, alcohol, and ether) is being used by the Air Mail Service and is proving advantageous in operation characteristics and over-all economy, engine overhauling for carbon removal being much less frequent.

(*c*) The results of the long series of tests completed last year and including different grades of gasoline for use as aircraft engine fuels have been analyzed and a report prepared covering these results. In general it has been found that for different grades of gasoline there are only very unimportant differences in horsepower when proper vaporization and mixing of the air and fuel are secured.

IV. Lubricants.

The committee has undertaken directly no work in connection with the study of lubricants, but is in close cooperation with the lubrication research undertaken during the year by the Bureau of Standards for the War Department. This program has included the establishment of a very complete lubrication laboratory, work being begun actively in February, 1919. Besides the routine testing of new and used oils in connection with service test in airplane engines, the laboratory is engaged in the development of improved methods of analysis and tests of lubricating oils, including investigation of the tests of demulsification, oxidation, absorption of gasoline and other fuels. A comprehensive series of service tests of oils in aircraft engines has been completed.

A new type of friction-testing machine has been designed and built, capable of making tests on aircraft engine bearings of all the usual designs.

REPORT OF COMMITTEE ON MATERIALS FOR AIRCRAFT.

The work of the committee on materials for aircraft during the past year has been hampered somewhat by the disorganization which followed the cessation of hostilities. Many of the investigations have, however, been continued, principally those for the improvement of the metals used in aircraft construction, particularly the light alloys, those for the use of metal to replace wood and fabric in wing construction and those for the improvement of aircraft fabrics.

1. *Corrosion of painted and unpainted aluminum sheets in sea water.*—On the reorganization of the committees of the National Advisory Committee for Aeronautics, the light alloys committee was abolished and the work previously carried out by that committee was transferred to the committee on materials for aircraft. One of the researches pending was the study of corrosion in sea water of painted and unpainted aluminum alloy metal plates, in which were included, in addition, some of the ordinary metals of commerce, such as copper, iron Muntz metal, etc. These plates were mounted and exposed between high and low tides in sea water at the following navy yards: Portsmouth, N. H., Norfolk, Va., and Pensacola, Fla. After three

months' exposure these were dismounted and the results of the observations are being prepared for publication. The most interesting fact relating to the aluminum and duraluminum plates is that the unpainted and painted sheets both stood up very well, showing very little effect of corrosion and demonstrating that it is not necessary to paint aluminum sheets for seaplanes, etc. The presence of oil in the water in one of the navy yards probably has influenced some of the detailed results.

2. Pure aluminum.—The committee on light alloys considered that it was of very considerable importance to obtain aluminum as free as possible from the usual impurities of iron and silica, thus affording a basis for a structural study of such alloys as duraluminum. This work is progressing at the Bureau of Standards.

3. Metal airplane construction.—The work done on metal airplane wing construction during the war was successful, although the designs which proved satisfactory were perfected too late to be produced in quantities. It is believed, however, that the foundation is laid for the manufacture of metal wing structures for commercial planes as soon as they are required in quantities which will warrant the expense necessary to provide tools, dies, etc.

Further tests could, however, be advantageously made on wing structures for which steel tubing is used for the flanges and lattice members for the beams.

4. Fireproof wing covering.—The study of fireproof wing coverings and also of transparent wing coverings has been undertaken at the Bureau of Standards. The theoretical study of this problem, now practically completed, shows that several methods of constructing a fireproof covering appear feasible. Experiments to determine their strength and resistance to combustion are now in progress.

5. Transparent wing covering.—The problem of securing transparent covering, especially if it is to be noninflammable, is of unusual difficulty, principally due to the poor optical properties of such a film and the probability that it will lack strength. These are matters which are receiving careful study and upon which it is believed that definite conclusions will be reached in the near future.

6. Fabrics for aircraft.—Most of the work was a study of tautness, tear resistance, and dope penetration. The development of a heavy fabric for large airplanes was also undertaken, as well as the development of a light-weight balloon fabric in which an investigation was made of the variation of permeability of the fabric for fabrics having different thread counts.

None of these important researches is yet finished, but all are being pushed to completion as rapidly as conditions will permit.

Among the problems which are considered worthy of careful study are some of the many suggestions and designs for reinforced airplane fabrics.

Little work has been done on airplane dopes and varnishes during the past year.

Subcommittees.—In order to carry on the work of the committee more effectively, three subcommittees have been formed. They are:

Subcommittee 1: Metals.
Subcommittee 2: Woods and glue.
Subcommittee 3: Coverings, dopes, and protective coverings.

TECHNICAL REPORTS.

The first annual report of the committee contained technical reports Nos. 1 to 7; the second annual report, Nos. 8 to 12; the third annual report, Nos. 13 to 23; the fourth annual report, Nos. 24 to 50; with this, the fifth annual report, the committee submits the following technical reports, Nos. 51 to 82:

Report No. 51, entitled "Spark Plug Defects and Tests," by F. B. Silsbee, of the Bureau of Standards. The successful operation of the spark plug depends to a large extent on the gas tightness of the plug. Part I of this report describes the method used for measuring the gas tightness of aviation spark plugs. Part II, entitled "Methods for Tests of Spark Plugs," describes the methods used in testing the electrical conductivity of the insulation material when hot, the testing of the cold dielectric strength of the insulation material, the resistance to mechanical shock, and the final engine test.

Report No. 52, entitled "Temperatures in Spark Plugs having Steel and Brass Shells," by C. S. Cragoe, of the Bureau of Standards. The report embodies the results of measurements taken of the electrodes and insulators of spark plugs of different types while they were in actual operation. The data throw considerable light upon the problem of the proper control of temperatures in these parts.

Report No. 53, entitlted "Properties and Preparation of Ceramic Insulators for Spark Plugs." Part I, "Methods of Measuring Resistance of Insulators at High Temperatures," by F. B. Silsbee and R. K. Honaman, of the Bureau of Standards, describes in some detail the preliminary experiments which were made on the conductivity of spark-plug insulators in order to develop a satisfactory comparative method for testing various spark-plug materials. Part II, "Electrical Resistance of Various Insulating Materials at High Temperatures," by R. K. Honaman and E. L. Fonseca, of the Bureau of Standards, gives data showing the characteristics of various porcelains and other materials when subjected to a high temperature, which is to cause the current to flow through the body of the plug instead of sparking at the terminals. Part III, "Preparation and Composition of Ceramic Bodies for Spark Plug Insulators," by A. V. Bleininger, of the Bureau of Standards, gives the composition of a number of porcelains developed by the Bureau of Standards suitable for spark-plug purposes. Part IV, "Cements for Spark Plug Electrodes," by H. F. Staley, of the Bureau of Standards, gives the results of an investigation to obtain the best possible cement to hold the nickel electrode wire in the porcelain body of a spark plug.

Report No. 54, entitled "Effect of Temperature and Pressure on the Sparking Voltage," by F. B. Silsbee and L. B. Loeb, of the Bureau of Standards. This report presents the results of an investigation which was to determine how the voltage necessary to produce the proper spark discharge varies with the pressure and temperature of the gas in which the discharge takes place.

Report No. 55, entitled "Investigation of the Muffling Problem for Airplane Engines," by G. B. Upton and Victor R. Gage, of Cornell University. The importance of eliminating the noise of the engine by some muffling device has been thoroughly appreciated. This report deals with experiments in the development of a muffler designed on an entirely new principle, which will give the maximum muffling effect with a minimum loss of power.

Report No. 56, entitled "Heat Energy of Various Ignition Sparks." Part I, "Method of Measuring Heat Energy of Ignition Sparks," by F. B. Silsbee, L. B. Loeb, and E. L. Fonseca, of the Bureau of Standards, describes a method developed at the Bureau of Standards for measuring the total energy liberated as heat in a spark gap by an ignition system, and gives a means of measuring the effectiveness of an ignition device as an electric generator. Part II, "Measurement of Heat Energy per Spark of Various Ignition Systems," by F. B. Silsbee and E. L. Fonseca, gives the results of direct measurements in absolute units of the total heat supplied to a spark gap by ignition systems of different types operating at various speeds, under conditions substantially equivalent to those in the cylinder of a high-compression aviation engine.

Report No. 57, entitled "The Subsidiary Gap as a Means for Improving Ignition," by W. S. Gorton, of the Bureau of Standards. This report presents the results of an investigation into the utility, action, and design of the auxiliary spark gap as a means for insuring freedom from spark plug failure due to fouling, and also to enable the restarting of fouled plugs.

Report No. 58, "Characteristics of High-Tension Magnetos," by F. B. Silsbee, of the Bureau of Standards, gives the results of an investigation made into the fundamentel physical characteristics of high-tension ignition megnetos, and also describes the methods used for measuring the quantities involved.

Report No. 59, entitled "General Analysis of Airplane Radiator Problems," by H. C. Dickinson, W. S. James, and R. V. Kleinschmidt, of the Bureau of Standards, embodies the results of a very extensive research, both theoretical and experimental, into the problems involved in the dissipation of heat by means of the airplane radiator.

Report No. 60, entitled "General Discussion of Test Methods for Radiators," by H. C. Dickinson, W. S. James, and W. B. Brown, of the Bureau of Standards, describes the methods and apparatus developed and used in the extensive experimental research into the problems involved in the dissipation of heat by means of the airplane radiator.

Report No. 61, entitled "Head Resistance Due to Radiators," by R. V. Kleinschmidt and S. R. Parsons, of the Bureau of Standards, gives the results of experimental determinations of head resistance of a wide variety of radiator cores, and also of three forms of complete radiators. Special attention should be called to the value of the wing radiator and of the radiator located in the open, especially when the latter is provided with a properly designed streamlined casing.

Report No. 62, entitled "Effect of Altitude on Radiator Performance," by W. S. James and S. R. Parsons, was prepared at the Bureau of Standards, and gives the results of a study of the effect of reduced pressure and temperature upon the capacity of airplane radiators.

Report No. 63, entitled "Results of Tests on Radiators for Aircraft Engines," by H. C. Dickinson, W. S. James, and R. V. Kleinschmidt. Part I of this report presents the results of tests on 56 types of cores, in a form convenient for use in the study of the performance and of the possible improvements in existing designs. Part II gives the results of some extensive experimental determinations of the resistance to the flow of circulating water through a wide variety of radiator cores. These data are of special value in evaluating the hydraulic head against which the circulating pump is required to operate.

Report No. 64, entitled "Experimental Research on Air Propellers, III," by W. F. Durand and E. P. Lesley, is a continuation of a report on the same subject published in the fourth annual report of this committee, and has been prepared by Prof. E. P. Lesley, of Leland Stanford Junior University. It states the results of investigations made upon numerous propeller models at the request of this committee, and contains valuable data to those interested in the design of air propellers.

Report No. 65, entitled "The Kiln Drying of Woods for Airplanes," by Harry D. Tiemann, of the Forest Products Laboratory. This report is descriptive of various methods used in the kiln drying of woods for airplanes and gives the results of physical tests on different types of woods after being dried by the various kiln-drying methods.

Report No. 66, entitled "Glues Used in Airplane Parts," by S. W. Allen and T. R. Truax, embodies the results of research on the glues used in the manufacture of wooden airplane parts, conducted by the Forest Products Laboratory of the United States Forest Service. The methods described for the testing of the physical properties of the different types of glues are of considerable interest and value.

Report No. 67, entitled "Supplies and Production of Aircraft Woods," by W. N. Sparhawk, forest examiner, Forest Service, Department of Agriculture. The purport of this report is to present in brief form such information as is available regarding the supplies of the kinds of wood that have been used or seem likely to become important in the construction of airplanes, and also a general statement of the uses to which each kind of wood is or may be put.

Report No. 68, "The Effect of Kiln Drying on the Strength of Airplane Woods," by T. R. C. Wilson, of the Forest Products Laboratory, is a very complete treatise on the comparative strength of air and kiln dried wood. The series of tests included 26 species of wood, approximately 100 kiln runs, and over 10,000 mechanical tests.

Report No. 69, entitled "A Study of Airplane Ranges and Useful Loads," by Dr. J. G. Coffin, of the Curtiss Engineering Corporation, is an analysis of the maximum flight radii of typical large airplanes and a discussion of the way in which the possible length of flight is affected by the change of weight by consumption of fuel during the flight.

Report No. 70, entitled "Preliminary Report on Free Flight Tests," by Edward P. Warner and F. H. Norton, of the advisory committee's staff at Langley Field, relates to some simple studies on the lift and drag characteristics and longitudinal balance and stability of an airplane, as determined by measurements in flight.

Report No. 71, entitled "Slip-Stream Corrections in Performance Computation," by Edward P. Warner, is an analysis of experiments performed by Eiffel on the air velocity in the slip stream of a propeller, and also includes a theoretical discussion of the magnitude of this velocity in different propellers.

Report No. 72, entitled "Wind Tunnel Balances," by Edward P. Warner and F. H. Norton, embodies a description of the balance designed and constructed for the use of the National Advisory Committee for Aeronautics at Langley Field, and also deals with the theory of sensitivity of balances and with the errors to which wind tunnel balances of various types are subject.

Report No. 73, entitled "The Design of Wind Tunnels and Wind Tunnel Propellers," by Edward P. Warner, F. H. Norton, and C. M. Hebbert, discusses the theory of energy losses in wind tunnels, the application of the Drzewiecki theory of propeller design to wind tunnel propellers, and the efficiency and steadiness of flow in model tunnels of various types.

Report No. 74, entitled "Construction of Models for Tests in Winds Tunnels," by F. H. Norton, deals with the methods of constructing aerofoils and all other parts of a model airplane, including discussion of the degree of accuracy required.

Report No. 75, entitled "The Aerodynamic Properties of Thick Aerofoils Suitable for Internal Bracing," by F. H. Norton, relates to some experiments performed at the wind tunnel of the Massachusetts Institute of Technology. The report includes the results of tests on a number of aerofoils, both straight and tapered, of constant and variable form, most of the sections being derived from the "Durand No. 13" as a basis.

Report No. 76, entitled "Analysis of Fuselage Stresses," by Edward P. Warner and R. G. Miller, is devoted to a discussion of the conditions of loading to which a fuselage may be subjected and to comparative analysis of a typical fuselage under seven different sets of loading conditions.

Report No. 77, entitled "The Parker Variable Camber Wing," by H. F. Parker. This report deals with the problem of increasing the speed range of an airplane by varying the camber of a wing surface. The variable camber wing offers many advantages over the variable incidence type of speed range.

Report No. 78, entitled "The Limiting Velocity in Falling from a Great Height," by Prof. E. B. Wilson, of the Massachusetts Institute of Technology, is a simple treatment of the problem, showing that the fundamental characteristic of the vertical motion under gavity in a resisting medium is the approach to a terminal or limiting velocity, whether the initial downward velocity is less or greater than the limiting velocity.

Report No. 79, entitled "Bomb Trajectories," by Prof. E. B. Wilson, of the Massachusetts Institute of Technology, is a mathematical treatise dealing with the trajectories of bombs of high terminal velocity, dropped from a great altitude.

Report No. 80, entitled "Stability of the Parachute and Helicopter," by H. Bateman, of Throop College of Technology, deals with an extension of the theory of stability in oscillation to the case of aircraft following a vertical trajectory, and particularly to the oscillations of parachutes.

Report No. 81, entitled "Comparison of United States and British Standard Pitot-Static Tubes," by Dr. A. F. Zahm and R. H. Smith. The results shown in this report give a comprehensive comparison of the accuracy of United States and British standard Pitot tubes.

Report No. 82, entitled "Airplane Stress Analysis," by Dr. A. F. Zahm, is a textbook on stresses in all parts of the airplane and in all sorts of trusses, and contains a number of illustrative examples.

FINANCIAL REPORT.

The appropriation "National Advisory Committee for Aeronautics, 1919," carried in the sundry civil appropriation act, approved July 1, 1918, is as follows:

For scientific research, technical investigations, and special reports in the field of aeronautics, including the necessary laboratory and technical assistants; traveling expenses of members and employees; office supplies, printing, and other miscellaneous expenses; equipment, maintenance, and operation of research laboratory and construction of additional buildings necessary in connection therewith; personal services in the field and in the District of Columbia:

Provided, That the sum to be paid out of this appropriation for clerical, drafting, watchmen, and messenger service for the fiscal year ending June thirtieth, nineteen hundred and nineteen, shall not exceed $43,000; in all, $200,000, of which sum $10,300 shall be available for printing and binding the bibliography of aeronautics from July first, nineteen hundred and nine, to December thrity-first, nineteen hundred and sixteen: *Provided*, That the Secretary of War is authorized and directed to furnish office space to the National Advisory Committee for Aeronautics in governmental buildings occupied by the Signal Corps.

This sum, added to the continuing appropriation of $5,000 a year for five years, carried in the act establishing the committee, made a total of $205,000 available for the fiscal year 1919.

Out of this total appropriation of $205,000 for the expenses of the committee for the fiscal year 1919, the committee reports expenditures and obligations during the year amounting to $204,381.27 itemized as follows:

Salaries (including engineering staff)	$59,789.03
Wages	5,868.68
Equipment	45,651.24
Supplies	25,255.14
Transportation and communication	1,000.28
Travel	4,722.01
Special investigations and reports	24,298.37
Construction of buildings	37,796.45
Total	204,381.27

Appropriation for the fiscal year 1920.—The appropriation "National Advisory Committee for Aeronautics, 1920," carried in the sundry civil act, approved July 19, 1919, is as follows:

For scientific research, technical investigations, and special reports in the field of aeronautics, including the necessary laboratory and technical assistants; traveling expenses of members and employees; office supplies, printing, and other miscellaneous expenses, including technical periodicals and books of refernce; equipment, maintenance, and operation of research laboratory and wind tunnel, and construction of additional buildings necessary in connection therewith; not to exceed $1,500 for the purchase, maintenace, and operation of one motor-propelled passenger-carrying vehicle; personal services in the field and in the District of Columbia: *Provided*, That the sum to be paid out of this appropriation for clerical, drafting, watchmen, and messenger service for the fiscal year ending June 30, 1920, shall not exceed $43,000; in all, $175,000.

Estimates for the fiscal year 1921.—The following estimates of expenditures for the fiscal year 1921 have been submitted by the committee in due form:

For scientific research, technical investigations, and special reports in the field of aeronautics, including the necessary laboratory and technical assistants; traveling expenses of members and employees; office supplies, printing, and other miscellaneous expenses, including technical periodicals and books of reference; equipment, maintenance, and operation of research and dynamometer laboratories and wind tunnel, and construction of additional buildings necessary in connection therewith; construction and equipment of necessary temporary quarters at Langley Field for civilian employees; maintenance and operation of one motor-propelled passenger-carrying vehicle, and purchase, maintenance, and operation of one motor-propelled passenger-carrying motorcycle; personal services in the field and in the District of Columbia: *Provided*, That the sum to be paid out of this appropriation for clerical, drafting, watchmen, and messenger service for the fiscal year ending June 30, 1921, shall not exceed $65,000; in all, $437,000.

CONCLUSION.

The science and art of aeronautics made wonderful progress during the war, due to the stimulus of necessity. Over 11,000 aviators were trained in this country, with a loss of 264 lives in training, and more than 13,000 airplanes were constructed in the United States. There were great delays, however, in getting an effective air force into action during the war, due primarily to the general lack of preparation for war, but particularly due to the lack of a proper scientific and technical foundation before the war.

From the lessons of the war we know that aeronautics will be the first arm of defense and of offense to come into action in future wars. Victory will sharply incline to the side that establishes superiority in the air, though its other forces may be relatively weaker than the enemy's. It follows that serious losses in industry, personnel, supplies, and communication can easily be inflicted on the enemy, and a decided superiority in the air, once attained, will be difficult to overcome.

Several European nations are making strenuous efforts and comparatively large peace-time expenditures to develop aeronautics and to maintain a trained reserve personnel. In America we have a force of reserve military aviators, but our peace-time expenditures for the maintenance of an aircraft industry and the further development of aeronautics are small. The committee invites the attention of the Congress to the need for providing encouragement for the development of commercial aviation, as well as military aviation, and to the need for more liberal support of scientific research and experimental work in aeronautics. There are many practical problems involved in the development of aeronautics commercially, and the commercial development, aside from being its own reward, will be a distinct military asset in time of war, and should therefore be encouraged and guided as far as practicable by the Government. In this connection the remarkable record of the Air Mail Service is encouraging. In the first place the Post Office Department sought and obtained the advice of the National Advisory Committee for Aeronautics, and through it obtained material assistance from other agencies of the Government, particularly the Signal Corps of the Army. Its continued independent development should be encouraged.

To summarize the more immediate and important matters, the committee strongly recommends to the Congress:

First. That liberal support be given to the estimates and programs for the development of military, naval, and postal air services.

Second. That greater support be given to the National Advisory Committee for Aeronautics in its program for the continuous scientific study of the problems of flight. This is particularly desirable because of the great increase in the number and importance of the problems to be solved and the reduced volume of experimental work conducted by other agencies since the signing of the armistice. Greater direct support of scientific research and experimental work in aeronautics becomes a necessity in view of the limited appropriations for the Army and Navy Air Services and the consequently limited encouragement and limited ability of the aircraft industry to conduct experimental and development work.

Third. That special steps be taken at once through the proper governmental channels to encourage foreign trade in aircraft. The committee suggests that it may be advisable to send a special aeronautical mission to South American countries to create markets for American aircraft and to interest and advise the commercial attachés of the Department of Commerce and the consular agents of the State Department as to the possibilities of aeronautics in those countries and the ability of the American aircraft manufacturers to meet the needs.

Fourth. That every practicable encouragement be given by the Federal Government to the establishment of landing fields in and by municipalities generally, and as near the centers of activity as possible. The committee especially suggests that the War Department be authorized to cooperate with the various municipalities at least to the extent of aiding in the layout and marking of the fields and the placing of at least one hangar on each field.

Fifth. That legislation be enacted for the regulation of civil aerial navigation, of the issuance of licenses to pilots, of inspection of aircraft, of uses of landing fields, etc., that the enforcement of regulations be placed under the Department of Commerce, and that, pending enactment of definite regulations by Congress, a board of representatives of various Government departments and of this committee be authorized to prepare such regulations for the approval of the Secretary of Commerce. The committee believes that air navigation should be regulated in much the same manner as marine navigation, and recommends the above as purely temporary legislation.

Sixth. That a continuing program for the construction of aircraft for the various governmental services be authorized, so as to assure, through the apportionment of relatively small orders among manufacturers of aircraft, the existence of a nucleus of an aircraft industry capable of expansion to meet military needs in an emergency.

Respectfully submitted.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
JOSEPH S. AMES, *Chairman Executive Committee.*

REPORT No. 51

SPARK PLUG DEFECTS AND TESTS

Part I.—CAUSES OF FAILURE OF SPARK PLUGS

By F. B. SILSBEE

Part II.—GAS LEAKAGE IN SPARK PLUGS

By L. B. LOEB, L. G. SAWYER, and E. L. FONSECA

Part III.—METHODS FOR TESTING SPARK PLUGS

By H. C. DICKINSON, F. B. SILSBEE, and P. G. AGNEW

Bureau of Standards, Washington, D. C.

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REPORT No. 51.

PART I.

CAUSES OF FAILURE OF SPARK PLUGS.

By F. B. Silsbee.

RÉSUMÉ.

It is the purpose of this report to collect and correlate a considerable amount of information which has been accumulated at the Bureau of Standards for the National Advisory Committee for Aeronautics during the past two years relative to the causes of failure of spark plugs in aviation engines. It is hoped by defining the various types of failure to clarify the spark-plug problem and to be of assistance to the manufacturers in improving their designs. The characteristics of the ignition system used in aviation gasoline engines are such that only a certain maximum voltage can be produced by the system even on open circuit, and if the insulation between the spark-plug terminals is reduced the maximum voltage is correspondingly reduced and no spark will occur if the insulation is too low. The requirements which a spark plug must meet are, therefore,

1. The maintenance of a gap having a breakdown voltage of about 6,000 volts.
2. The maintenance of an insulation resistance of at least 100,000 ohms.
3. Practically complete gas tightness.

These requirements must be maintained under pressures of 500 to 600 pounds per square inch while immersed in a medium which alternates rapidly in temperature between 0 and 2,500° C., and in an atmosphere which tends to deposit soot upon the surface of the insulator. The various manners in which a spark plug may become inoperative may be enumerated as follows:

1. Fouling with carbon deposit causing short circuit.
2. Fouling with oil deposit causing open circuit.
3. Breaking of the insulator.
4. Preignition.
5. Conduction through the insulator.
6. Electrical puncture of the insulator.
7. Minor trouble, such as warping and breaking of electrodes, etc.

Experience in the altitude laboratory at the bureau and authoritative information received from France indicate that the first type of failure accounts for over 50 per cent of the trouble encountered in practice, particularly at high altitudes; the third type of failure accounts for nearly 40 per cent of the trouble; the second type of failure occurs quite frequently when first starting an engine, but very seldom develops after the engine is once running. The other types of failure are of relatively rare occurrence, but must be kept in mind in the design of spark plugs, since departure from the conventional designs is very liable to produce one or another of these types of failure.

In the report the cause and identification of each type of failure are described in detail and where possible remedies are suggested. These remedies are unfortunately so conflicting in character that no general conclusions can be drawn, and the design of a spark plug is in every case a matter of balancing the opposing requirements to suit conditions in the particular engine considered.

INTRODUCTION.

It is the purpose of this report to collect and correlate a considerable mass of data and information which has been accumulated at the Bureau of Standards during the past two years relative to the causes of failure of spark plugs in aviation engines. It is hoped by defining the various distinct types of failure which are liable to occur and by indicating their relative importance and, where possible, the remedies for them, at least to clarify the spark-plug problem and to be of some assistance to manufacturers in improving their designs. Owing to the fact that the various types of failure often require remedies which are conflicting in character, only general conclusions can be drawn, and any design of plug must require a balance between opposing factors, the relative importance of which depends upon the type of engine in which the plug is to be used.

The sources from which this data has been obtained are somewhat varied. There is at the Bureau of Standards an altitude laboratory in which aviation engines are tested while in a vacuum chamber, so arranged as to duplicate quite closely the conditions of operation in an airplane flying at high altitude. Records have been kept of a large number of spark plugs used in the engines which were being subjected to various tests in this chamber and the different spark plug troubles which occurred were noted. It is believed that the conditions of operation at any given altitude in this test chamber are entirely comparable with those in actual flight, but in studying the data it must be remembered that the proportion of the time at which the engine was operated at various altitudes may be somewhat different from that occurring in actual service in the field.

Laboratory tests have been made on a wide variety of plugs which are shown in the accompanying photographs. A description of the methods used in these laboratory tests will be found in Part III of this report. The purpose of these tests was to measure certain properties (gas tightness, mechanical strength, etc.) of the spark plugs of each type and to form a basis by which the relation between these various properties and the service performance could be correlated.

Results have also been secured of some extensive studies made in France at various flying fields of the American Expeditionary Forces on the performance of various French spark plugs in a number of French aviation engines. This work was under the supervision of Lieut. L. B. Loeb, who had previously been a member of the ignition staff of the Bureau of Standards and who was intimately familiar with the laboratory tests there conducted, and the data which he has supplied can be directly compared with data obtained in this laboratory.

In addition to these three principal sources, numerous conferences have been held with aviation officers and engine builders, as well as with spark plug manufacturers.

CONDITIONS OF OPERATION.

The usual type of ignition system used with gasoline engines consists essentially of an induction coil, the primary current of which may be provided either from a battery or by the motion of the coil itself in the field of a permanent magnet, as is the case in the high-tension magneto. In either case, the essential features of the operation of this type of device are, first, that with its secondary circuit open the voltage of the coil will build up to a certain definite limit, approximately 10,000 to 20,000 volts; and, second, if the secondary is closed, either through a shunting resistance or through a spark gap which is broken down and is permitting the passage of a current of electricity, then the maximum current delivered by the secondary of the coil is limited to a value of from 0.05 to 0.10 ampere. In many cases the maximum voltage of the system is limited by a safety gap to a value somewhat less than the inherent limit referred to above, which is fixed by the inductance and capacity of the circuit and the current at "break."

The voltage required to produce a spark in the cylinder of a high-compression aviation engine is approximately 6,000 volts. (For a discussion of the effect of the pressure and temperature of the gas on this voltage, see Report No. 54.) Consequently, when the spark plug is

clean, there is a considerable factor of safety. If the plug is shunted by even a very high resistance, the maximum voltage reached is materially reduced and with a lower value of resistance than about 100,000 ohms, the voltage may be insufficient to produce a spark. The magnitude of the effect of a shunting resistance may be estimated from the relation that the voltage across the plug previous to the passage of the spark is equal to the product of the shunting resistance by the current flowing through it. Thus, for example, if the secondary current of the coil is limited to 0.08 ampere and the shunting resistance is 50,000 ohms, the maximum voltage available is only 4,000 volts and no spark will occur. The requirements of the spark plugs are, therefore, to maintain a gap the sparking voltage of which does not greatly exceed 6,000 volts, and to maintain an insulation resistance across this gap which is considerably greater than 100,000 ohms. The plug must also be gas tight under the conditions of pressure and temperature existing in the engine.

While much remains to be learned as to the conditions existing in modern aviation engines, the pressures and temperatures met with are roughly as follows: The pressure on the plug alternates between a slight suction during the intake stroke and a pressure of 500 to 600 pounds per square inch during the expansion stroke. There is a considerable vibration of the engine as a whole, which is at times sufficient to crack porcelain insulators. In rotary engines the centrifugal force acting on any part situated near the periphery may exceed 500 times the weight of that part. The incoming charge of gas mixture during the intake stroke may be several degrees below zero in cold weather or at high altitudes, while the flame of compressed and burning gas which surrounds the plug during the expansion stroke may reach a temperature of 2,500° C. These alternations of pressure and temperature occur with a frequency of about 15 cycles per second, and the fluctuations in temperature can not penetrate to any appreciable depth in the insulating material of the plug. The resultant effect is that the inner end of the insulator and central electrode reach an average temperature of approximately 900° C.; the body of the insulator well up in the shell seldom exceeds 200° C.; and the shell itself is in contact with a jacket containing water at 70° C. (Report No. 52 gives some data on temperatures observed in spark plugs with brass and steel shells when operating in aviation engines.)

The various manners in which a spark plug may fail to operate under the conditions just described may be enumerated as follows:

(1) Fouling with carbon deposit causing short circuit.
(2) Fouling with oil deposit causing open circuit.
(3) Breaking of the insulator.
(4) Preignition.
(5) Conduction through the insulator.
(6) Electrical puncture of the insulator.
(7) Minor trouble, such as warping and breaking of electrodes, etc.

DISCUSSION OF TROUBLES.

These classes of failure will be discussed in detail in the following paragraphs:

(1) *Fouling by carbon deposits.*—This trouble is due to the deposit of a layer of carbon upon the surface of the insulator or to the formation of a cake of carbon immediately between the electrode surfaces. This carbon is due to two causes: (*a*) The chilling of the flame by a cool portion of the plug, which thus renders combustion incomplete. This effect is particularly common when the mixture of gasoline and air is too rich in gasoline and is consequently of frequent occurrence in operation at high altitudes in cases where the carburetor is not properly compensated for the decrease in density of the atmosphere at those altitudes. (*b*) The second cause for carbon deposit is from the decomposition of lubricating oil which may be splashed or sprayed on heated portions of the insulator. The lubricating oil itself is an electrical insulator, and when it wets a layer of soot on the spark plug it tends, by surrounding each particle of carbon, to make the entire mass an insulator. Gradually, however, such a deposit chars under the action of the flame and becomes more and more conducting.

In this process the oil acts as a binding material for the soot and also increases the rate of deposition, because particles of carbon in the flame may adhere to the oily surface instead of remaining in suspension in the flame and burning later in the stroke. The conduction through the deposit thus formed seems to take place along a narrow path where the oil film between the particles has been broken down by the electric stress rather than as a uniform conduction over the whole surface of the insulator.

This trouble seems to be the most frequent source of failure of spark plugs. Records kept in the altitude laboratory show over 50 per cent of the spark plug troubles to be due to this cause.

The reports from France also corroborate this statement. As would be expected, the trouble is more serious at high altitudes than at low, and seems to occur more readily with mica than with porcelain plugs. This is probably due to the somewhat rough surface of the mica, which causes the carbon to adhere more readily.

While the engine is in operation, such fouling causes misfiring of the cylinders, or, in case there are two plugs in one cylinder, one of which remains clean, there is merely a slight loss in engine power. On removing the plugs from the cylinder a heavy deposit of carbon is at once evident. It should be noted that spark plugs may appear very black and heavily sooted and yet show a high resistance, owing to the fact that the carbon particles are not in direct contact but may be insulated with a film of oil. After long use porcelain insulators frequently take on a film of reddish-brown color, which, however, does not tend to short circuit the plug and which must be distinguished from fouling with carbon.

The possible remedies for this type of failure lie (*a*) in improving the design of the plug (*b*) in improving the carburetor system, and (*c*) in modifying the ignition system.

(*a*) The insulator of the spark plug may be so shaped by the use of petticoats, ridges, or a long conical projection that a portion of this surface operates at a very high temperature. With this arrangement all carbon deposit is burned off during the early part of the combustion of the charge, while the gas in the cylinder still contains an excess of oxygen. This type of construction is particularly useful in engines which are well cooled, but in engines which are very hot and of high compression normally, this construction may tend to cause preignition. An alternative method of design is shielding the insulator with a metal baffle plate, which prevents the access of oil and its resulting carbonization. This is useful in engines in which a large amount of oil is used, or in which the plug is so located as to be particularly exposed to a spray of oil. With this construction, however, there is usually little opportunity for a carbon deposit to be burned off, and if such a plug happens to become fouled at light load or high altitude, it will not come back into service at full load or low altitude.

(*b*) It is probable that the development of new types of carburetors which is now in progress will greatly reduce the occurrence of excessively rich mixtures in planes flying at great altitudes and will thus tend to reduce this source of trouble.

(*c*) Certain special types of ignition systems have been devised which are particularly suited for firing plugs which are shunted with a fairly low resistance. The usual arrangements of such systems is to connect an auxiliary spark gap in series with the spark plug. (A discussion of the use of such systems will be found in Report No. 57.) With devices of this type, it has been found possible to produce regular firing in an engine in which the plugs were deliberately fouled so as to have an insulation resistance of only 5,000 ohms.

(2) *Fouling with oil.*—This trouble occurs in cases where the lubricating oil forms a coating over the surface of the electrodes or forms an actual drop between the electrode points. Since the breakdown strength of oil is several times that of air, the voltage required to produce a spark under these conditions is very greatly increased and may exceed the voltage which the ignition system is capable of delivering. If the insulation of the spark plug is at the same time somewhat reduced by the presence of soot, the maximum voltage which the system will give correspondingly reduced.

This trouble usually occurs when there is an excessive amount of lubricating oil in the cylinder and this condition arises most frequently on starting an engine when it has been turned

over several times with no flame in the cylinder which might serve to burn off the film of oil. The condition is also met with when the plane is recovering from a long glide, during which the engine was turning over slowly and pumping oil into the cylinders. This trouble is particularly annoying to mechanics in charge of aviation engines, since it occurs at starting when they are working on the engine, and it frequently gives a bad reputation to an otherwise good plug. It is rather rare, however, that the trouble arises in an engine after it has once been started. The trouble may sometimes be identified by the firing of the magneto through its safety gap, thus indicating that the voltage required to pass a spark at the plug is greater than that required to break down the safety gap. On removing the plugs from the engine when failure has occurred from this cause they will be found wet with fairly clean oil.

The remedies for this trouble are found in modifying the design of the electrodes. A number of shapes have been used as shown in the photographs, which serve to drain the oil away from the spark gap by capillary forces. Experience with various French plugs has indicated that this trouble occurs most frequently in plugs in which one electrode consists of the wall of the spark plug shell as in the Ponsot, Joli, and Rudex plugs.

The trouble is, of course, reduced by avoiding excessive amounts of lubricating oil in the cylinders and by occasionally opening the throttle of the engine while making long glides and thus burning out the accumulated oil before the amount has become excessive. This procedure is common practice. Certain types of high frequency ignition systems have been devised which are capable of giving a much greater voltage than the ordinary types of system, and with these the trouble from oil fouling would probably be much reduced. None of these systems is at present in common use so that no field experience is available.

(3) *Cracking of insulator.*—Any crack in the body of the insulating material may permit the passage of the spark from the central electrode to the shell in such a location that it does not cause ignition of the explosive gas mixture. The thickness of the insulating wall in many plugs is so great that a spark will not pass directly through a clean crack in the insulator and the engine may run for some time even when the plug is badly cracked. In time, however, the cracks in the interior of the plug become filled with carbon from the flame and will finally conduct sufficient current to prevent sparking at the electrodes. Of course, any broken pieces of porcelain which may be cracked from the insulator are very detrimental to the engine.

The factors which may cause cracking are several. The mean temperature gradient from the hot inner end of the insulator to the relatively cold shell causes the hotter portions of the insulator to expand to a greater extent than the cooler, and sets up stresses in the insulator itself which may cause cracking. Such cracks are particularly likely to originate where there is a sudden change in diameter of the insulator, as at the shoulder. Also if the metal parts are so placed that their greater expansion tends to produce pressure on the relatively less expansible insulator, cracks may occur as a result. It is probable that in some cases actual drops of relatively cool lubricating oil may strike the hot parts of the insulator and by suddenly chilling them cause cracks. There seems to be good evidence that in some engines the mechanical vibration of the engine as a whole is sufficiently rapid and intense to break the porcelain from purely mechanical causes. Such breakage often occurs in the outer part of the porcelain at the plane of the bushing or crimping. An impact testing machine has been constructed at the Bureau of Standards in which the spark plug under test is screwed firmly into the side of a steel block which is arranged to strike repeatedly against a steel anvil. The velocity of the block and plug at the instant of impact is about 200 cm. per second and the blows occur at the rate of 300 per minute. (For details of this machine, see Part III.) Certain types of plugs which gave trouble from cracking in service, also cracked when tested in this impact machine, the location and character of the crack, though different for the different types of plug, being the same in both the engine and laboratory tests for a given type. Since no heat was applied in the laboratory tests, it seems probable that the mechanical shock was the main cause of cracking in these cases.

There is also a considerable breakage of plugs due to accidently striking them with a wrench or other tool when inserting them in the engine.

In the Bureau of Standards' laboratory approximately 40 per cent of the failures which occurred with porcelain plugs were due to cracking of the insulator. The reports from France indicate that considerable trouble has been experienced from this cause, and that as a result mica plugs are much more popular, and only a relatively small proportion of porcelain plugs are now used in that country. A plug which has failed in this manner usually shows continuous misfirings, although in the case of a small crack the missing may be irregular. On removal of the spark plug, the crack may often be located by the grating sound heard when the plug is strained by the fingers, in cases where no crack is visible at the surface.

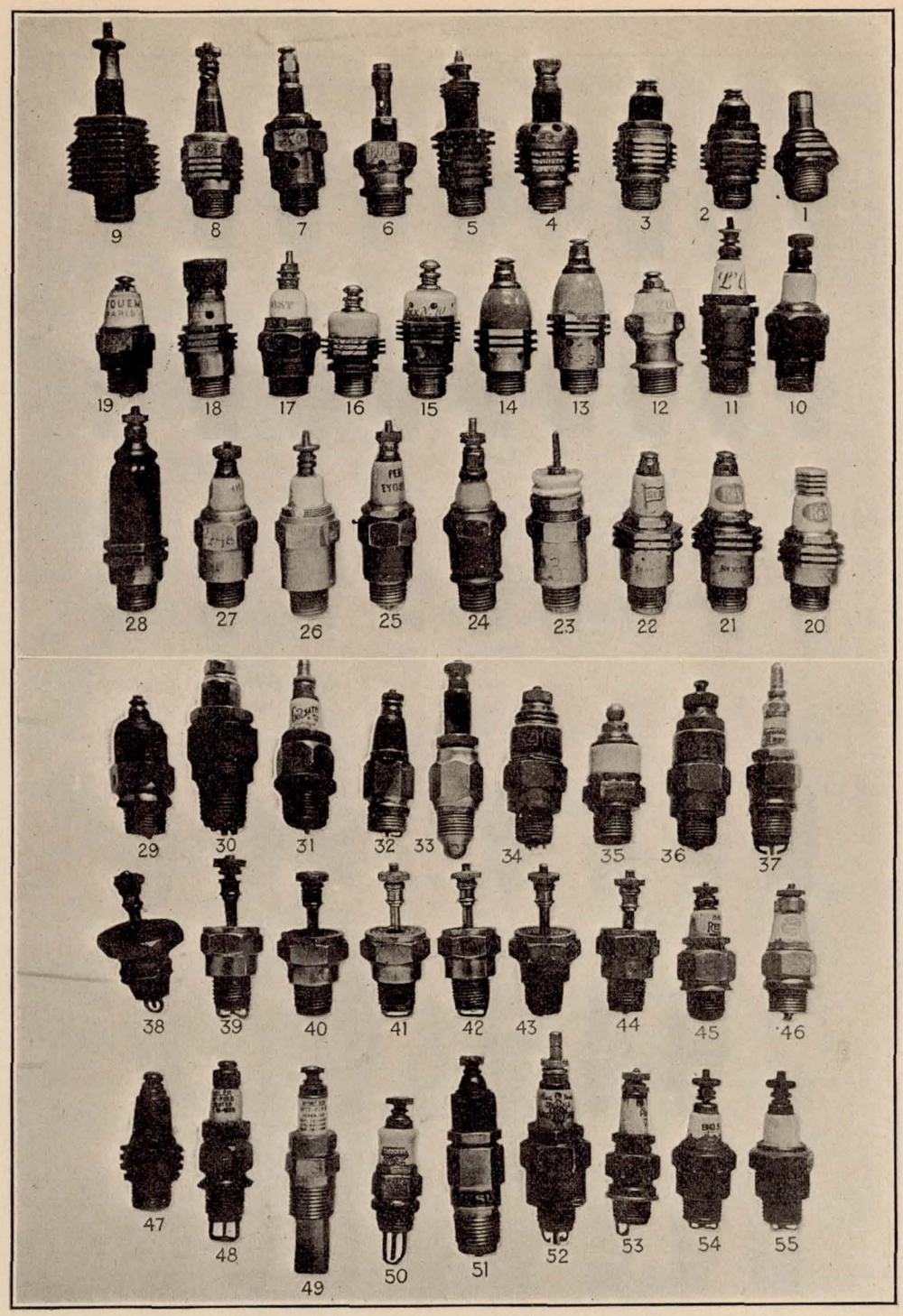
Mica plugs are, of course, practically free from this source of trouble and the most obvious remedy with porcelain plugs is to use a material which shall combine at the same time a high mechanical strength, a low modulus of elasticity, a low coefficient of thermal expansion, and a high thermal conductivity. During the past two years very considerable progress has been made by a number of porcelain manufacturers in developing insulating materials which are superior in these respects to those formerly used. (Report No. 53, Part III, contains a description of a development of one of these types which was carried out at the ceramic laboratory of the Bureau of Standards.)

Certain plug designers have endeavored to avoid trouble from this source by making their insulator in two or more pieces as is done in the Pognon and Duffy spark plugs. In these plugs the innermost porcelain attains a relatively high temperature and expands correspondingly while the outer pieces are cooler and expand only slightly. The passage of a spark between the central electrode and the shell through the joint between the porcelain sections is prevented by a wrapping of mica around the interior of the shell and around the electrode, respectively. It is, however, very difficult to make plugs of this type gas tight.

In plugs in which the central electrode is cemented in the porcelain throughout the greater part of its length, it is essential that the diameter of the electrode be kept small in order that the total amount of its thermal expansion may be taken care of by a yielding of the cement without setting up excessive strain in the inclosing porcelain. Closed-end plugs serve to reduce the trouble from the spraying of drops of cold oil upon the hot insulator, and the resulting splitting off of bits of porcelain. They also tend to prevent any broken pieces of porcelain from getting into the engine cylinder.

Breaking of the insulator by the mechanical vibration of the engine seems to be materially reduced if the insulator is cushioned by a considerable thickness of packing material, such as asbestos, placed between the shoulder of the insulator and the bushing. The plugs in which the edge of the shell is crimped over the shoulder of the insulator, commonly called the one-piece type, have given considerable trouble from cracking of the porcelain at the edge of the shell. This effect seems to be due in part to the rigid connection between the shell and the porcelain, which transmits the mechanical shock of the engine without any cushioning, and in part to stresses set up in the porcelain by the shrinking of the metallic shell after it has been heated during the process of crimping. These troubles can be materially reduced by proper design of the tool used in making the joint. Variations in the proportions of the plug make a decided difference in its resistance to breaking from mechanical shocks. Two extreme types of design are illustrated in plugs 74 and 76. Though these were both of the same material, the long and slender porcelain gave decidedly more trouble from this cause.

4. *Preignition.*—This trouble, when chargeable to the spark plugs, is the result of too high temperatures occurring at some part of the plug, either the tip of the insulator or end of the electrode, or other small projection, resulting in ignition of the charge in the cylinder before the end of the compression stroke. Preignition may occur from several causes not connected with the spark plugs, as for instance, from overheated portions of the combustion chamber, such as hot exhaust valves, from hot points or flakes of carbon or other material lodged in the cylinder and heated by compression of the charge adiabatically to a temperature where ignition occurs spontaneously. There is probably a definite relation between the maximum compression pressure and the tendency to preignite from hot points, since the higher the compression the more readily is the charge ignited.



TYPES OF SPARK PLUGS SUBMITTED FOR TEST.

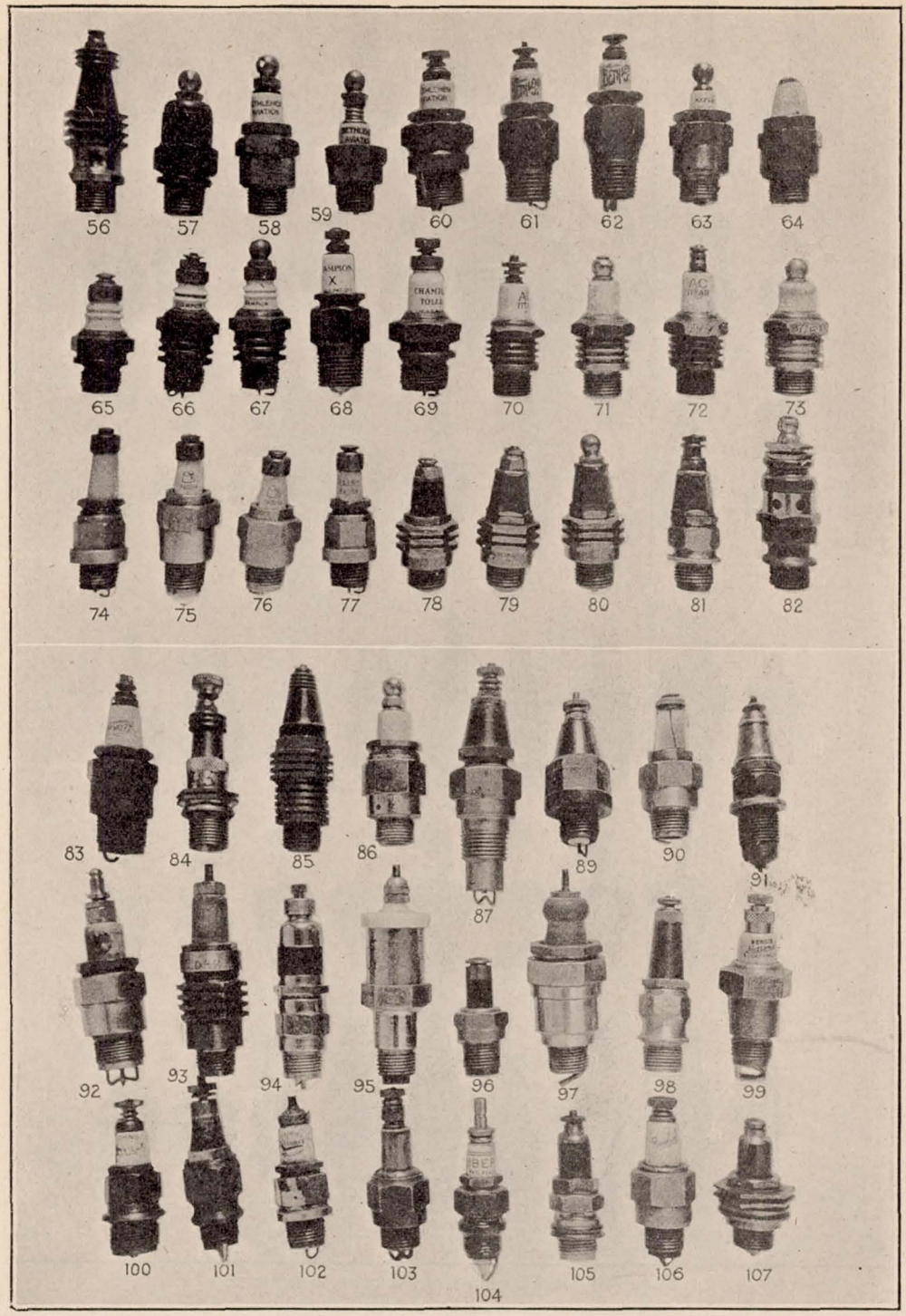
[Foreign plugs are of French manufacture unless otherwise stated.]

1, Ruillet.
2, Oleo (brass).
3, Oleo (steel).
4, Frigo.
5, Lodge (British).
6, Pola.
7, Conill.
8, O. L. M. (Italian).
9. Renault.
10, Aris.
11, L'As.
12, L'As.
13, Eole.
14, Eole.
15, Rudex.
16, Rudex.
17, Benoist.
18, Leda.
19, Eyquem.
20, R.e V.
21, R. e V.
22, Serb.
23, Pognon.
24, Joly.
25, Fert (Eyquem).
26, D. A. D.
27, Oleo (Proc.).
28, A. C. F. (Italian).

AMERICAN PLUGS.

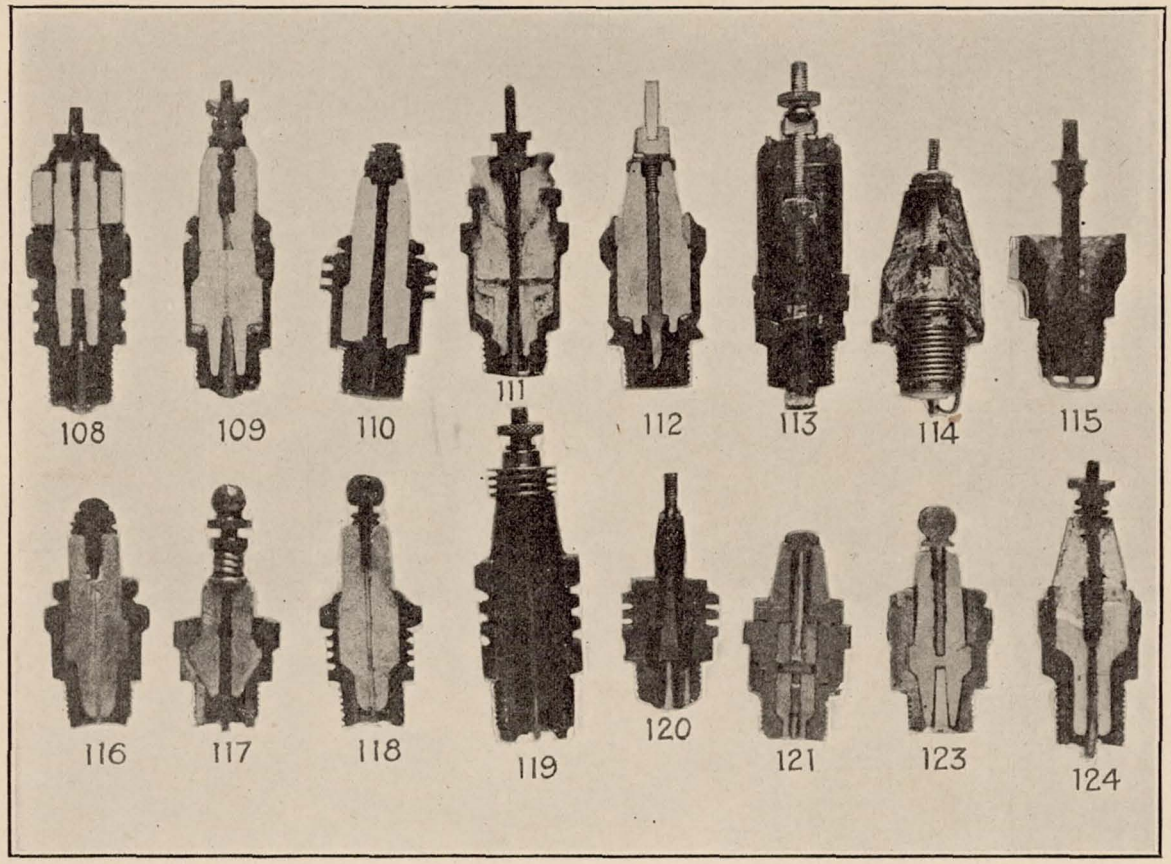
29, Sharp (Ponsot type).
30, Sharp (Kopper King).
31, Sharp (Goliath).
32, Sharp (motorcycle).
33, Sharp (closed end).
34, Herz (Steatite).
35, Herz (Ponsot).
36, Herz (Steatite).
37, Stewart (V-ray).
38, Anderson (hollow core).
39, Anderson (ring insert).
40, Anderson (closed end).
41, Anderson (hollow end).
42, Anderson (ridged end).
43, Anderson (flush end).
44, Anderson (nipple).
45, Reflex (Baby).
46, Auburn (Wright).
47, Mosler (Le Rhone).
48, Mosler.
49, Mosler (spitfire).
50, Mosler (Vesuvius).
51, Mosler (Vesuvius).
52, Red Head (Big Boy).
53, Red Head.
54, Bosch (American).
55, Bosch (German).

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TYPES OF SPARK PLUGS (Continued).

56, Bethlehem (de luxe).
57, Bethlehem (Ponsot).
58, Bethlehem (aviation).
59, Bethlehem (Bugatti).
60, "
61, "
62, "
63, Duffy (air line).
64, Duffy (3-piece).
65, Champion (small).
66, Champion (aviation).
67, Champion (Liberty).
68, Champion (X).
69, Champion.
70, Titan.
71, Titan.
72, Titan.
73, Titan.
74, Rajah (long porce).
75, Rajah (closed end).
76, Rajah (open end).
77, Rajah (short porce).
78, Splitdorf (mica top).
79, Splitdorf (Le Rhone).
80, Splitdorf (Le Rhone).
81, Splitdorf (open end).
82, Splitdorf (Ponsot).
83, Affinity.
84, Sullivan.
85, Siebert.
86, St. Louis (Valve).
87, Benford (Golden giant).
89, Minogue.
90, Corning.
91, Benton.
92, Hercules.
93, Hercules.
94, Walden-Worcester.
95, Randall.
96, Pittsfield.
97, Express.
98, Campbell.
99, National.
100, Johns Manville.
101, Latch.
102, Reliance.
103, Anchor.
104, Liberty.
105, Comet.
106, Berkshire (Porc.).
107, Berkshire (Mica).



CROSS SECTIONS OF TYPICAL SPARK PLUGS.

108, Herz.
109, Fert.
110, R. e V.
111, Pognon.
112, Joly.
113, A. C. F.
114, Minogue.
115, Anderson.
116, Bethlehem.
117, Bugatti.
118, Titan.
119, Bethlehem (de luxe).
120, Splitdorf.
121, Duffy (3-piece).
123, Duffy (air line).
124, Bosch (German)

The importance of this cause of trouble seems to have been somewhat overestimated. It has been observed only in rare cases in the engines tested at the Bureau of Standards, and reports from France show it to be of minor importance. In cases where the spark plugs are leaky and are consequently unduly heated by the passage of gas through them, temperatures which will cause preignition, however, may often be attained. The danger of preignition, moreover, limits the extent to which the design of spark plugs can be modified in the direction of maintaining high temperatures, and prevents the use of otherwise desirable designs which would operate at such high temperatures as to insure the burning off of the deposits of carbon.

Definite identification of this source of trouble is quite difficult without the use of an engine indicator, but mechanics familiar with the running of the engine can often judge by the noise and vibration when preignition is occurring. In some cases ignition from overheated plugs may occur before the inlet valve has closed. This results in the familiar "popping back" in the carburetor and may constitute a serious fire hazard on a plane. A careful distinction should be made between true preignition, and what may be called "afterfiring." This latter phenomenon consists in the continued operation of the engine after the ignition system has been cut off, as a result of the ignition of the charge from heated surfaces within the cylinder. Ignition from such surfaces is slow and has the effect of a greatly retarded spark. The combustion in such cases is relatively late, does not yield much power, and can maintain only a very slow engine speed. The pressures obtained by this effect probably occur so late in the stroke as not to interfere with the normal operation of the engine when the electric ignition is also functioning.

Remedies for preignition, as far as the spark plugs are concerned, are obviously to keep the insulator as cool as possible by making it short and compact. Long central electrodes should be avoided, and also constructions which tend to permit the formation of flakes of mica, which, owing to their low heat conductivity, will maintain their high temperature throughout the intake stroke. The use of a copper rod for the central electrode should be effective in this respect, but introduces difficulties from expansion and oxidation. Other extreme designs intended to eliminate preignition troubles have used a hollow central electrode containing a small quantity of mercury which, being vaporized at the inner end and condensing at the outer, greatly increases the effective heat conductivity of the electrode. Other designs of plugs have used check valves which allow cool air from without to be sucked past the insulator during the intake stroke, but which prevent leakage of gas outward during the remainder of the cycle. This latter design, however, has not proved practical. There seems to be good evidence that the exhaust valves operate at nearly as high temperatures as the spark plugs, and they are probably equally effective in producing preignition where this trouble exists.

(5) *Conduction through insulator.*—It has frequently been stated that cases of spark-plug failures in very hot engines may be attributed to the fact that at high temperatures the insulating materials used in the plug become to some extent conductors of electricity and reduce the insulation resistance below the critical value of about 100,000 ohms. Report No. 53, Parts I and II, describe a series of measurements of this property for various materials and indicate that there is a very considerable variation between different materials in this respect. As a result of an exhaustive study of the subject, however, it appears that only in extremely hot engines and in cases where the ignition system is unusually feeble is failure of ignition likely to occur from this cause. The early reports which were received concerning this cause of failure have not been confirmed by later information from France, and it appears that the importance of this cause of failure has been exaggerated. The remedies for this trouble are, of course, the use of material of high resistivity, such as fused quartz, mica, or some of the porcelains recently developed by the bureau and by certain manufacturers. An alternative remedy is to use an auxiliary spark gap in series with the spark plug, as in cases of carbon fouling.

(6) *Electrical puncture of the insulator.*—The possibility of a direct puncture of the material by the igniting voltage is of much interest, though difficult to study quantitatively. In considering this matter the two very different methods of possible electrical failure of an insulating material must be carefully distinguished, as much confusion has arisen from failure to do this. The first of these is usually called "dielectric breakdown." This is exemplified by the behavior

of a sample of porcelain tested cold by applying a known voltage and gradually raising this until at about 8,000 volts per millimeter a spark passes through the porcelain. The voltage thus observed is called the breakdown voltage of the material and has a fairly definite value. Under these conditions the leakage current through the sample, even just before the breakdown occurs, is very small, and the sample is therefore not heated and changed in its properties appreciably by the application of the test voltage.

The second type of failure may be called "conductive breakdown," and is exemplified by the behavior of a porcelain sample tested when hot, say, at 500° C. At this temperature the resistance of a centimeter cube of ordinary porcelain is about 100,000 ohms, and if a voltage of only 500 volts per millimeter (i. e., only one-twentieth of that in the preceding case) is applied the current flowing will be 50 milliamperes, and the power dissipated in the sample will be 250 watts. This would, of course, raise the temperature of the sample very rapidly (at the rate of about 100° C. per second), and the resistance would consequently drop still lower and the material would be fused and destroyed in a very short time. It can be shown that although there is a fairly definite value of voltage and temperature at which samples tested under identical conditions fail in this manner, yet these values depend very greatly on the conditions of the experiment, such as the rate of application of the voltage, the ease with which the samples can lose heat to the surroundings, etc., and that it is impossible to assign any definite breakdown voltage to the material when tested in this manner. It is evident that the two types of failure depend on entirely different properties of the material, and so far as is known there is no connection between the two.

When a porcelain is used in a spark plug it is subjected to rather peculiar electrical conditions. At the instant the contact breaker opens the voltage increases with extreme rapidity to a value of 6,000 volts. This, however, lasts only a few hundred-thousandths of a second. The spark gap then breaks down and the voltage drops to a few hundred volts and remains at that value several thousandths of a second. It then drops to zero and remains so for something like a fifteenth of a second when the cycle is repeated. The total power output of the ordinary ignition system is limited to a few watts, so it seems improbable that the second or conductive type of breakdown occurs in practice. The maximum voltage in operation is less than one-fifth of the dielectric breakdown strength of the porcelain when cold. It is, however, possible that this dielectric strength is greatly diminished at high temperatures and that consequently plugs may fail from this cause. If the insulator was punctured by the peak voltage, the rest of the discharge would be concentrated at the small region of failure and might well be sufficient to produce fused spots in the material.

Owing to the rather remote possibility of this type of failure and the experimental difficulty of producing in the laboratory dielectric breakdown without conductive breakdown, no measurements have been made of the dielectric breakdown strength of insulators when hot.

(7) *Minor troubles.*—In addition to the principal causes of failure discussed above, trouble is occasionally experienced from warping of the electrodes. This either short circuits the gap or increases it to such an extent that the breakdown voltage required is more than the ignition system can furnish. This trouble can be remedied by supporting the central electrode to within a short distance of the spark gap, but many plugs are on the market in which a great length of unsupported wire is used.

With prolonged use the surfaces of the electrodes gradually corrode away as a result of oxidation between the crystal grains.

With the alloy usually used (Ni 97 per cent, Mn 3 per cent) this corrosion is very slow and the life of the plug is almost invariably limited by one of the other types of failure. It is stated, however, that slight impurities in the electrode wire greatly accelerate the rate of corrosion. If the construction of the plug is such that the material is subjected to a mechanical tension, the intercrystalline cracks are pulled apart and the deterioration is much more rapid. Tungsten has been suggested as an electrode material and would appear to be well suited because of its high melting point, low coefficient of expansion, and high heat conductivity. Preliminary tests at this bureau in which sparking was produced for a long period between tungsten elec-

trodes in an atmosphere of CO, showed very little corrosion. The extreme hardness and rigidity of the metal, however, makes it difficult to handle in manufacture, and its adoption for commercial use is probably not warranted.

In some cases a chemical corrosion of the electrode which ultimately causes the tip to drop off has been produced by a reaction between the material of the cement and the metal of the electrode at the high temperatures of operation. This matter has been discussed in Report No. 53, Part IV, and can be remedied by the use of suitable cements.

There seems to be some evidence that with very rich mixtures a deposit of carbon may be built out on the electrode surfaces themselves to such an extent as to short circuit the gap. The heat energy of the spark itself is, however, usually sufficient to burn away such deposits.

Electrical brush discharge over the hot surface of the insulator is occasionally suggested as an explanation of spark-plug trouble. A study of this effect made in the laboratory, while not entirely conclusive, seems to indicate that it is not an important factor. Experiments at atmospheric pressure and high temperature show that a brush discharge which forms a delicate purple glow over the surface of the insulator is produced when sufficiently high voltage from an ignition system is applied to a spark-plug insulator. The voltage required, however, is more than enough to cause a spark to jump from the central electrode to the shell. Experiments at higher pressures (see Report No. 54) and at temperatures up to 760° C. showed no trace of brush discharge in a plug having a gap width of 2.2 mm., although the pressure was raised to such a value as to require a sparking voltage of about 14,000 volts. The data at hand indicate that the increase in pressure in the engine cylinder is as effective in preventing the brush as it is the spark discharge. Consequently the former might develop only in case there were a layer of gas near the insulator which was decidedly hotter and less dense than the gas in the spark gap. Such a condition is very improbable in view of the turbulent motion of the cylinder contents.

GAS LEAKAGE.

Leakage of gas through the spark plug is never in practice sufficiently great to interfere with the operation of the engine directly. It does, however, tend to heat the spark plug very rapidly and causes one or another of the various types of failure discussed above. Part II of this report gives the results of experiments on the gas tightness of a variety of spark plugs, and describes the methods of test which have been found useful. The general conclusions reached as a result of this work are that tightness is much more a matter of workmanship than of design and that a wide variation is to be expected in the tightness of plugs made to the same design and even by the same manufacturer.

NOTES ON PLUG DESIGN.

It will be noted from the preceding discussion that the remedy suggested for one cause of failure is very often directly opposite to that suggested for another, and the proper design of a spark plug becomes a matter of balancing the conflicting requirements. The conditions in various types of engines vary quite widely, some having much higher operating temperatures than others and some having much greater amount of lubricating oil present in the combustion space than others. The type of spark plug which is suitable for one class of engine may fail to operate another.

The following general statements, however, seem to be justified by the information available. As to the material of the insulator, mica has the great advantage that it will not crack as a result of temperature gradient or other reason. Porcelain, however, is definitely superior in resisting the formation of deposits of carbon and is also much less expensive to manufacture. It may be said in general that the mica plug has to be of very good grade and workmanship to compete with a good porcelain plug, but is definitely superior to a plug with a poor grade of porcelain.

Assuming equally good workmanship, the method of making the joint between insulator and shell seems to have little effect upon the gas tightness of a plug except in certain designs

where the insulator is molded into the shell, in which case absolute tightness can be secured. The process of crimping the shell around the shoulder of the porcelain is very liable to set up strains and cause cracking of the insulator, but has the advantage of cheapness and rapidity of construction.

The shape and arrangement of the electrodes seem to have but little effect upon the operation of the plug, with the notable exception that plugs in which the side wall of the shell forms one electrode are definitely more liable to foul with oil and make starting difficult. The breakdown voltage of the spark gap depends to some extent upon the shape of the electrode tips, but such variation in breakdown voltage is comparatively slight and can be compensated for by a very slight difference in the length of the spark gap. The use of rather fine wires as electrodes tends to ease in starting as any oil film is readily burnt off, but is liable to cause preignition in hot engines. The use of a central electrode consisting of a disk or similar shape seems to have little advantage as far as the spark gap is concerned, for while it slightly reduces the likelihood that all possible sparking points may be fouled with oil simultaneously, the danger of short circuiting at least one of the many possible sparking points with carbon is correspondingly increased. The merits which this type of electrode may have lie in the protection which it may afford to the insulating material back of it.

Improvements to be expected in the construction of spark plugs seem to be along the lines of better porcelain bodies which are less likely to crack and the construction of a molded or fused insulator which will insure absolute gas tightness. There seems to be also a very considerable field for improvement in ignition systems so that they will be able to fire a spark plug even when it does not maintain the high insulation resistance which is required by the systems now in use. There is a great need of definite and accurate statistical data as to the performance of spark plugs of different types in various engines under service conditions, as it is only on the basis of such data that the real worth of any design can be determined, and it is only by the compilation of much larger amounts of such data than are now at hand that more definite conclusions as to the proper type of design can be based.

REPORT No. 51.

PART II.

GAS LEAKAGE IN SPARK PLUGS.

By L. B. Loeb, L. G. Sawyer, and E. L. Fonseca.

RÉSUMÉ.

This report describes the method used at the Bureau of Standards for measuring the gas tightness of aviation spark plugs, and gives the results of numerous measurements by this method The plugs to be tested are screwed into a pressure bomb and subjected to an air pressure of 225 pounds per square inch while submerged in oil heated to a temperature of 150° C. (302° F.). The leakage of air is then measured by the displacement of oil in an inverted bell jar placed over the plugs. Tables and curves contained in the report give the results of measurements taken on a wide variety of plugs under the above conditions, as well as data obtained with other values of pressure and temperature.

The data obtained are listed in Table I, and have been analyzed to bring out any relation which might exist between the gas tightness and the type of construction. For this purpose the types of construction were grouped into five classes, and the average leakage computed for each. Table II shows that there is comparatively little difference between the various classes and hence indicates that gas tightness is much more dependent upon workmanship than upon design. This is borne out by many tests.

Successive measurements on a single plug fail to repeat, which is due to permanent deformation of the shell, gaskets, etc. Also a wide variation is found among supposedly similar plugs from a single maker.

INTRODUCTION.

During the past year the Bureau of Standards has had occasion to test for gas tightness several hundred spark plugs of a wide variety of designs, both American and foreign. It is the object of this report to summarize the results of these tests, to record whatever conclusions can be drawn from the data thus obtained, and to describe in some detail the methods of test now used at the bureau.

The leakage of gas through a spark plug is negligible so far as the loss of pressure in the engine cylinder is concerned, but is of the greatest importance as regards the operation of the plug. A very slight leakage of the hot gases carries heat up into the body of the plug, rapidly raising its temperature, and thus causing one or another of a number of different types of failure which ultimately destroy the plug. Some practical engineers consider the gas tightness of a spark plug its sole important property.

The ordinary spark plug consists of three distinct parts, viz: The central electrode, the shell or outer electrode, and the insulating material, which is usually porcelain, mica, or glass There are thus in general two joints which must be made tight, though in some instances manufacturers have constructed both the central electrode and the insulator in two or more pieces.

METHODS OF TEST.

Various methods of test are now in use for factory inspection and for judging the relative merits of different types of spark plugs. For the former purpose many manufacturers test the

plugs while cold and with a pressure not over 100 pounds per square inch. In the case of spark plugs for special aviation work, all plugs are discarded which show any leakage on this test. Tests for determining the merits of different types are in general more severe.

Foreign military and aviation committees specify several different tests for gas leakage, two examples of which are as follows:

(1) The plug is tested for leakage through it, under cold oil, at an air pressure of 10 kilograms per square centimeter (142.1 pounds per square inch) for 15 minutes.

(2) Oil is pumped into a cylinder, into which the plugs are screwed, at a pressure of 30 kilograms per square centimeter (426.3 pounds per square inch), this pressure being maintained for 5 minutes. A pressure of 100 kilograms per square centimeter (1,421 pounds per square inch) is reported to have been reached in the case of one plug, but a plug is discarded if it leaks at the low pressure of 5 kilograms per square centimeter (71.05 pounds per square inch), the results at the higher pressures being of relative value only.

While on an engine in operation plugs are sometimes tested for gas tightness by spraying oil over them; but this test is not reliable, as the oil is likely to boil when it comes in contact with the hot plug, producing bubbles, thus making it difficult to tell whether it is heat or leakage that causes the bubbles.

The method used by the Bureau of Standards for determining gas leakage may be described as follows: The plugs to be tested are screwed into a pressure bomb, which is then filled with compressed air, while submerged in a bath of oil heated to any desired temperature. The leakage of air through the plug is measured by the displacement of oil in an inverted bell jar placed over the plug. Standard conditions for testing the relative merits of different types of plugs are 15 kilograms per square centimeter (225 pounds per square inch) air pressure and 150° C. (302° F.) temperature.

The apparatus used is shown in figure 1, and consists of a pressure bomb, an oil tank, two pressure tanks with pressure gauge, a graduated bell jar, and an aspirator. The pressure bomb is made from a piece of hexagonal steel with holes drilled and tapped to accommodate six spark plugs, as well as the pressure connection of one-eighth inch copper tubing. The bomb is suspended from both ends by iron straps, which are made fast to two upright standards securely fastened to the floor. The oil tank is of sufficient depth to completely submerge the bomb and plugs when the tank is raised. It is balanced by a weight attached to cords running over small sheave wheels, so as to slide up and down easily between the uprights which support the bomb. The tank contains a 1,000-watt heating coil.

Compressed air is obtained from a tank having a capacity of 150 cubic feet at an initial pressure of 1,500 pounds per square inch. Another smaller tank is used as a low-pressure reservoir, in order to maintain a steady pressure while making a measurement. The gauge used is an ordinary commercial pressure gauge reading to 500 pounds.

The graduated bell jar is made of Pyrex glass, and is about 2 inches in diameter and 7 inches long. The lower end of the jar has an opening equal to its full diameter, while the other end, drawn down to a diameter of approximately one-fourth inch, is closed by a rubber hose leading to the aspirator, as shown in figure 1. The jar is graduated at intervals, and the volume between successive marks is accurately known. In order to fill the bell jar the oil may be sucked up to the proper level by the mouth, but it is much more convenient to use a water aspirator, as shown in the drawing. This consists of an upright piece of iron pipe, closed at both ends, except for a small pipe connection at the top and bottom. The pipe at the bottom is so connected by valves to both the water supply and the sewer that the standpipe can be emptied or filled at will by the manipulation of these valves. The pipe at the top is connected to the bell jar by a rubber hose and water bottle, the purpose of the latter being to pick up any oil which might pass the bell jar.

In carrying out a measurement the plugs are screwed tightly into the bomb, against lead gaskets, instead of the usual copper-asbestos ones. The oil tank is then raised, submerging the bomb and plugs, and the oil drawn to the desired height in the bell jar, after which the

jar is sealed by a pinch cock on the rubber hose between the jar and the aspirator. When the pressure is applied, as the air leaks through the plug, the oil level in the bell jar gradually falls, and the time required for the level to travel between any two graduations is observed with a stop watch. The leakage in cubic centimeters per second can be readily determined from this

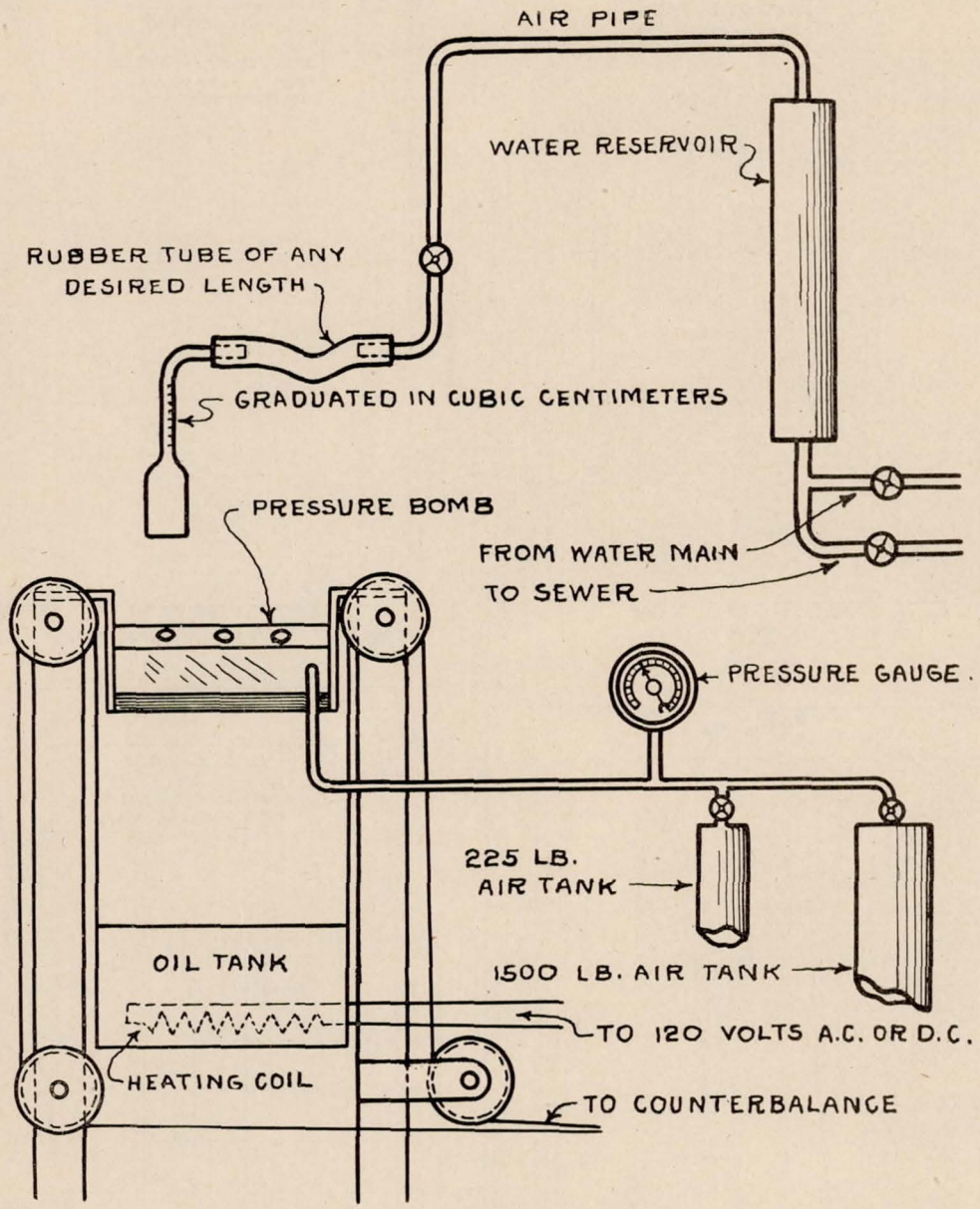
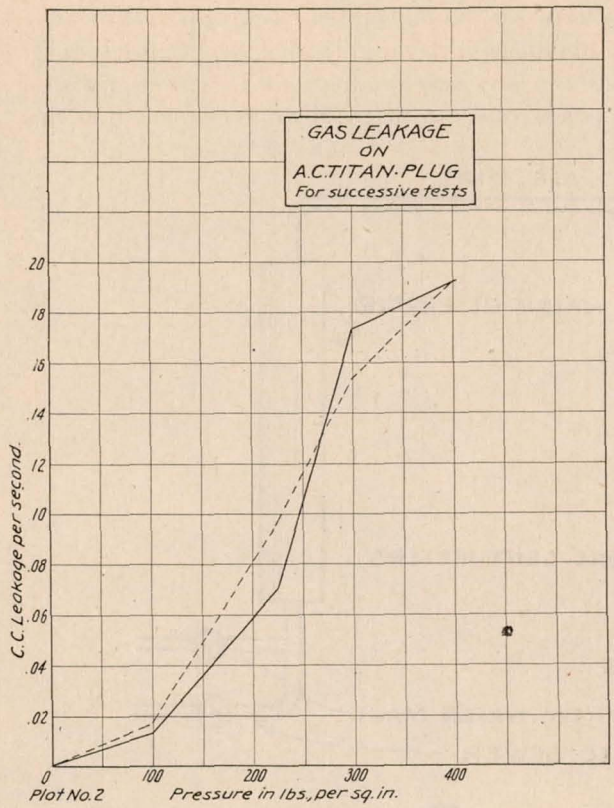


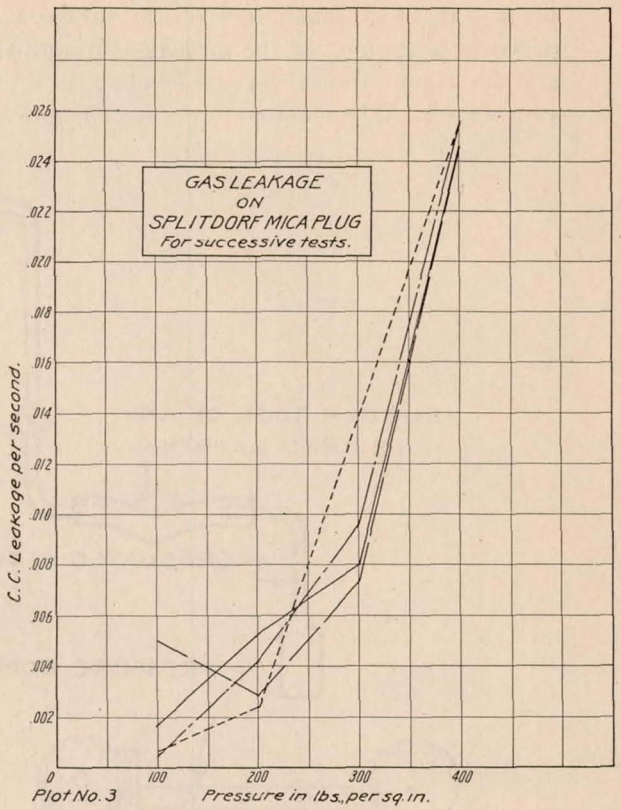
FIGURE 1.

time interval and the calibration of the jar. A leakage greater than 0.2 cubic centimeter (0.01 cubic inch) per second at a pressure of 15 kilograms per square centimeter (225 pounds per square inch) and at a temperature of 150° C. (302° F.) should be considered excessive for aviation work.

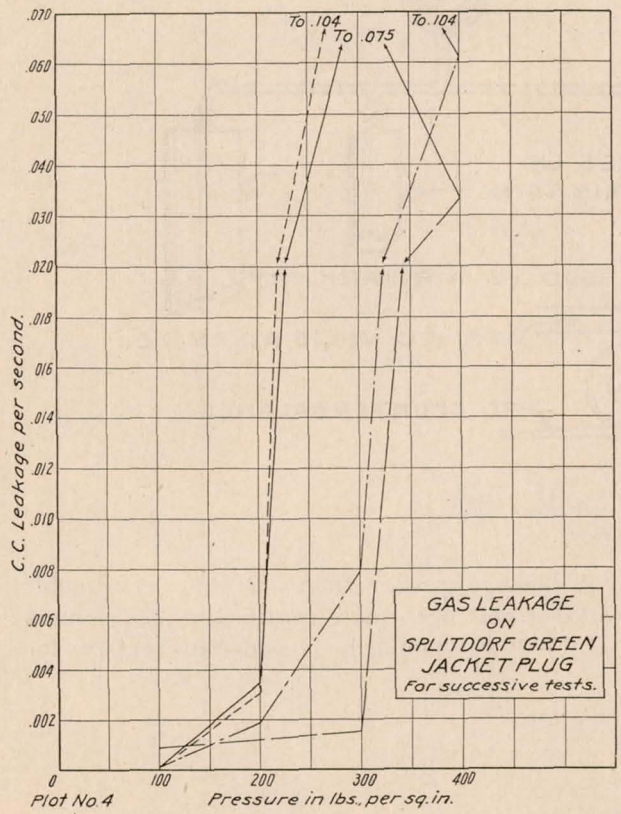
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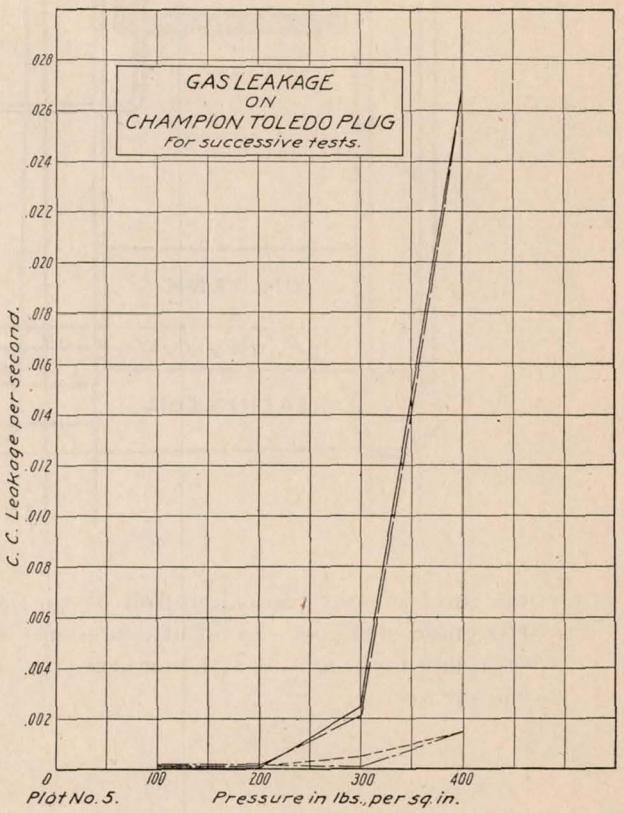
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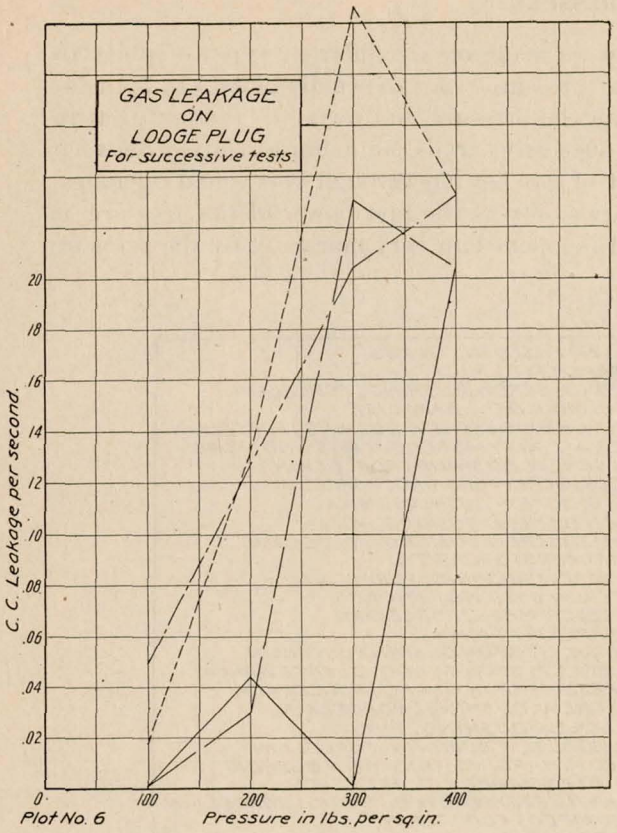
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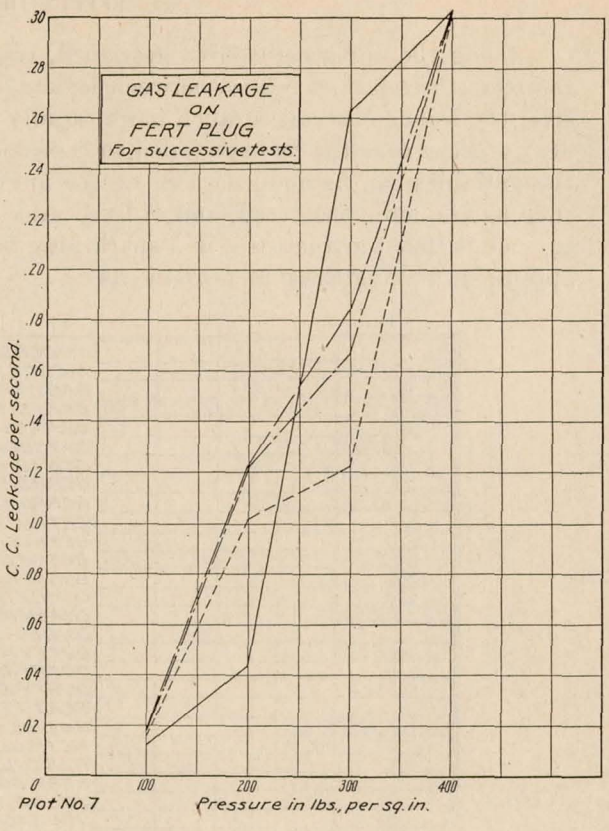
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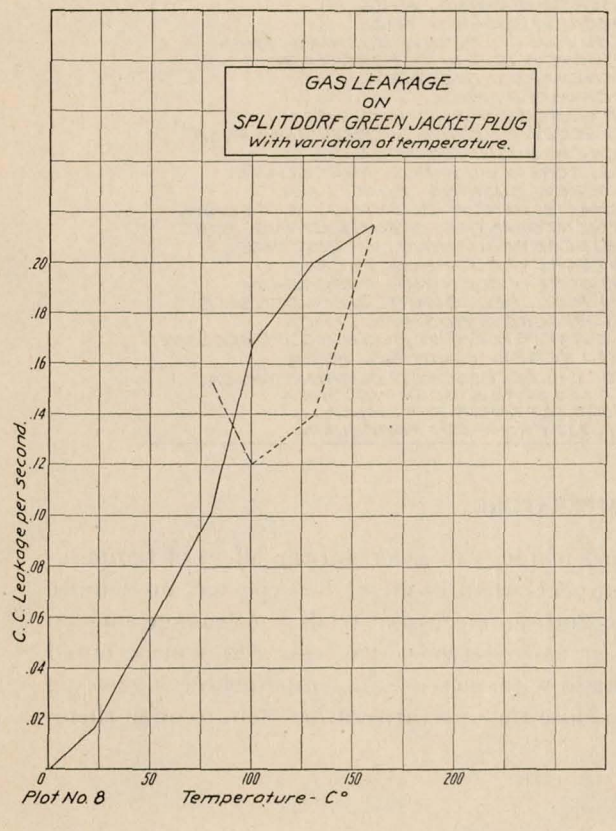
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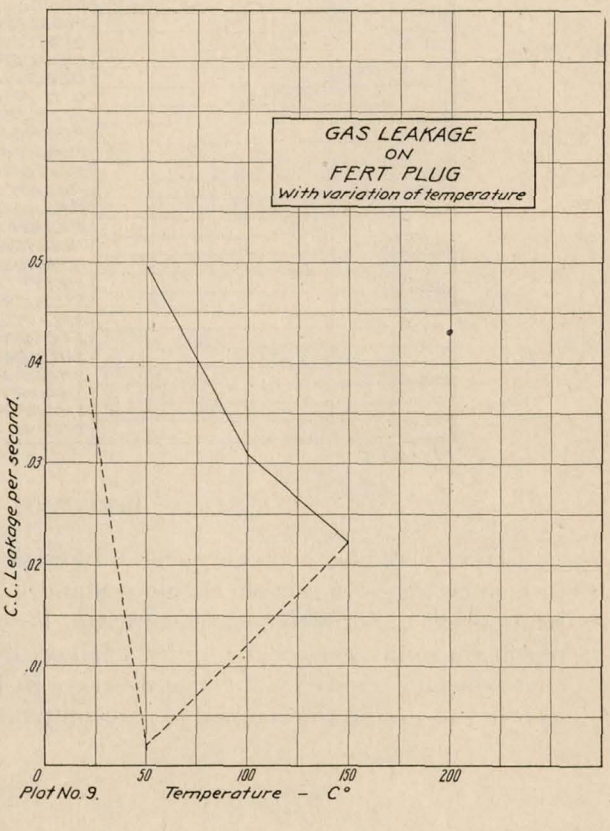
Plot No. 6



Plot No. 7



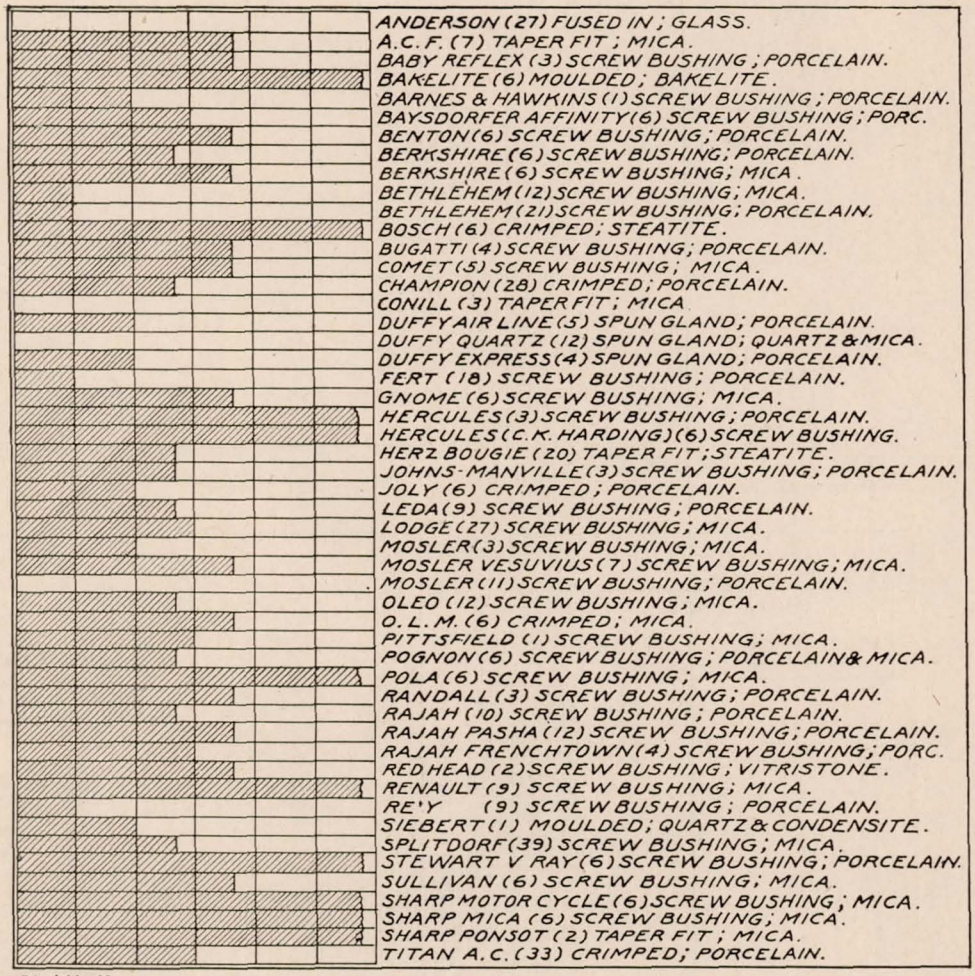
Plot No. 8



Plot No. 9.

EFFECT OF PRESSURE.

Using the apparatus above described, tests were made on six different types of plugs to ascertain the relation, if any, between leakage and pressure. As shown by plots 2 to 7, inclusive, the leakage increases much more rapidly than the pressure, but owing to the fact that in nearly every case the leakage failed to repeat on successive trials, no definite relation between the variables can be deduced. Since the amount of gas flowing through very small openings, such as are here considered, and of fixed area, varies only as the first power of the pressure, it is evident that the apertures in a spark plug must be opened up very markedly by the pressure applied in making these measurements.



Plot No. 10

EFFECT OF TEMPERATURE.

Tests were also made on several different types of plugs to ascertain the effect of temperature on leakage. As shown by plots 8 and 9, it appears that, as might be expected, no definite relation exists between temperature and leakage, and on successive trials the leakage fails to repeat, in some cases changing by a factor of 10 or more between two tests. It will be noted that one plug showed a definite decrease in leakage with increase in temperature, suggesting that in this design the thermal expansion tends to close the apertures rather than to open them.

RESULTS OF TESTS ON PLUGS.

The results of tests to determine the leakage of plugs cover such a wide range that in expressing the results it is more convenient to make seven classifications, as follows:

Class A, leakage below 0.005 cc. per second.
Class A−, leakage 0.005 to 0.01 cc. per second.
Class B+, leakage 0.01 to 0.10 cc. per second.
Class B, leakage 0.10 to 0.50 cc. per second.
Class B−, leakage 0.50 to 1.00 cc. per second.
Class C, leakage 1.00 to 5.00 cc. per second.
Class D, leakage over 5.00 cc. per second.

Table I and plot 10 show the average results for each of the various types tested, and also the number of plugs of each type. In studying these results one should bear in mind the variation to be expected in successive measurements of the same plug, also the variation among different plugs of the same manufacturer and shipment. This is illustrated by plot 11, which was plotted by dividing the 100 per cent base line into as many equal parts as there were plugs in each set, and then plotting the observed gas leakage of each plug as the ordinate at these equal intervals, choosing the plugs in the order of increasing leakage. Consequently the abscissa corresponding to any point on the graph indicates the percentage of plugs having less than the amount of leakage indicated by the ordinate at that point.

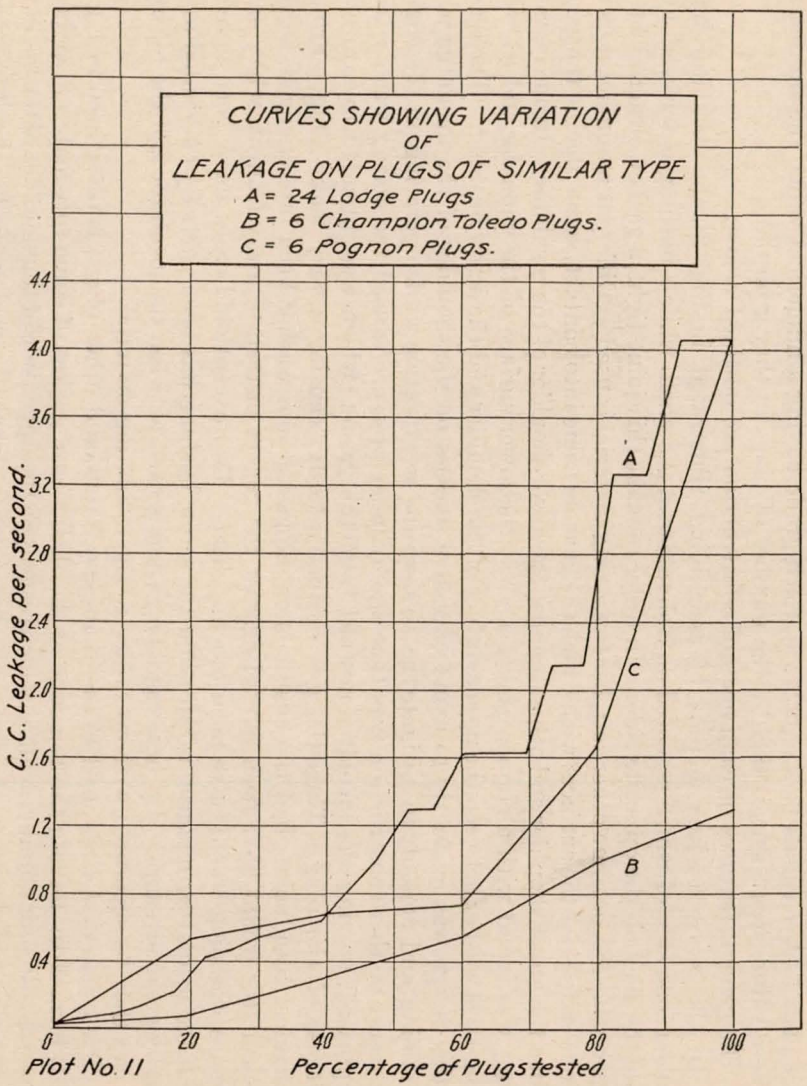
An endeavor was made, by analyzing the data contained in Table I, to determine whether there was, on the whole, any relation between the design of the plug and its gas tightness. For this purpose the plugs there listed were grouped into five classes, as follows: (1) screw bushing, (2) crimped, (3) taper fit, (4) molded, (5) spun gland.

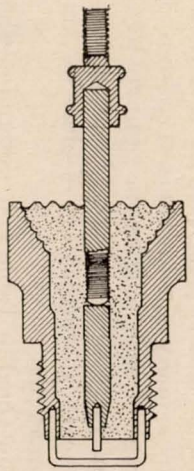
The average leakage for each class of construction was computed by assigning numerical values for various grades of leakage, as follows: D equals 1, C equals 2, B− equals 3, B equals 4, B+ equals 5, A− equals 6, A equals 7. Each grade having a numerical value, the summation of these values was then divided by the number of plugs in that group.

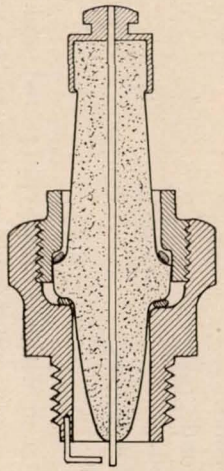
The general features of each class of construction are outlined below:

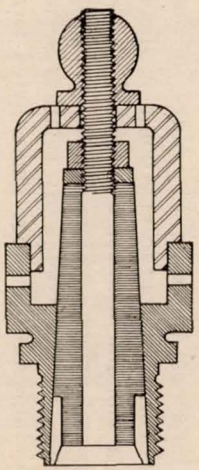
In the *screw bushing* method of assembling, illustrated in Fig. 13, the insulator has a shoulder, one side of which is seated on a shoulder in the shell, while a bushing is screwed down inside the shell on the opposite side. In order to make this joint tight, a gasket, either of brass, copper-asbestos, or some other soft, heat-resisting material is used. Different manufacturers use various shapes for the surfaces with which the gaskets come into contact, some placing the gasket against the upper shoulder and others against the lower shoulder of the insulator. In one instance a plug was found with a copper gasket against the lower surface of the shoulder and a slotted spring-steel washer between the upper surface of the shoulder and the screw bushing. The reason for this design was evidently to avoid excessive stresses on the shoulder of the insulator while assembling, and possibly to mitigate the stresses due to vibration while operating on the engine. The result of this construction was that the cylinder pressure caused the spring washer to be compressed, moving the insulator upward from the gasket, which was intended to insure the tightness of the plug. Thus the gas escaped readily, causing a very leaky plug. From a mechanical standpoint, had the positions of the gasket and washer been interchanged, so that the insulator would have been moved against the gasket instead of away from it, when under pressure, the plug would have been much tighter. Two exceptional cases have been noted in which the insulating material is mica and the screw bushing has been partially embedded in the mica by great pressure. In these cases no gasket is used between the insulator and the bushing, nor can they be separated without injury to the insulating material.

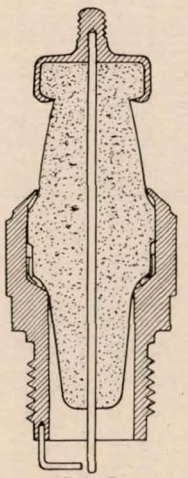
The *crimped shell*, as used in the Champion, Titan, and other plugs, is illustrated in Fig. 15 and is formed by forcing the top edge of the shell over a gasket of some soft material, as brass, copper-asbestos, or aluminum alloy, which rests upon the upper side of the shoulder of the insulator. These plugs give fairly good joints, but have never shown themselves to be absolutely tight, although in many cases the leakage was very small. This method of assembly has the disadvantage that the plug can not be taken apart for cleaning without destroying it.

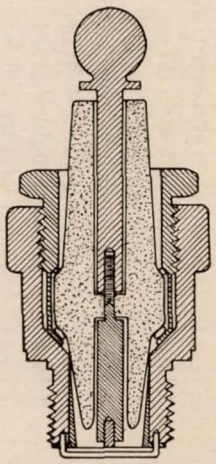



FIG. 12


FIG. 13


FIG. 14


FIG. 15


FIG. 16

The *taper fit* used by several manufacturers, Fig. 14, in all cases that have come to the attention of this bureau, were on plugs of mica or steatite insulation. The taper fit has failed in all cases but one to give a perfectly tight joint, this being due, undoubtedly, to the flaky property of the mica, which makes it very difficult to produce a smooth and hard surface that will stand the pressure exerted upon it when assembling the plug. One maker has overcome this difficulty by placing a thin steel jacket over the taper, which in this case is approximately 45°. This steel jacket is strong enough to withstand the pressure upon it, thus protecting the mica insulation, and at the same time is flexible enough to conform to the surface of the taper within the shell and form a perfectly tight fit.

The *molded-in* insulators, illustrated in Fig. 12, as represented by the Anderson plug, consist of glass which has been forced between the central electrode and the shell while in the molten state. It adheres to both the electrode and the shell, and forms an absolutely tight plug. Attempts have been made to use the molded materials, such as Bakelite and Condensite, in spark plugs; but, although these may produce a tight joint when cold, the samples thus far submitted have not been able to withstand the temperature conditions obtaining in actual service.

The *spun gland*, which is used upon only one type of plug, is as yet in the experimental stage. It is shown in Fig. 16. This plug uses a porcelain insulator, the shoulder of the porcelain being surrounded by a spun brass gland which is part of the screw bushing and projects a very little below the shoulder of the plug. The interior of the shell has a taper of 45°, which comes in contact with the edge of the gland. When the bushing is screwed down in the first assembly the edge of the gland is crimped about the shoulder of the porcelain, forcing a tight joint. This plug has the advantage of being easily taken apart for cleaning, and can be reassembled to give as tight a joint as at first without the aid of special wrenches. When the plug has once been assembled and the gland formed the insulator and bushing can not be separated without totally destroying the gland.

So far in the discussion of methods of assembly nothing has been said in regard to the numerous ways of assembling the central electrode and insulating material, which vary with different manufacturers. In the majority of cases the electrode is of uniform diameter throughout the entire length of the porcelain, having a shoulder on the inner end while the outer end is threaded and made tight by screwing a nut against a gasket or washer, the shoulder and washer both bearing on the insulator. In some instances both the electrode and insulator are threaded and screwed together, and a cement is introduced to insure a tight joint. In still other cases the electrode is cemented to the insulator, there being no other means of fastening these two parts together. Other manufacturers fuse or mold the electrode into the insulator.

There are certain objections to the use of any form of cement between the electrode and the insulator, the mechanical seal first described appearing to be the most satisfactory method of assembly. This matter is more fully discussed in Report No. 53, Part IV, entitled "Cements for Spark Plug Electrodes."

CONCLUSIONS.

The results obtained from the analysis of Table I are listed in Table II. It appears from this table that the molded insulator is definitely superior to the other types in the matter of gas tightness. The high rating of the spun gland type is somewhat questionable, since all the plugs tested were constructed especially for experimental purposes and did not represent a typical output on a production basis. The close agreement of the other classes, combined with the wide variations shown in Table I between different makes of the same class, show quite conclusively that the leakage depends much more upon the workmanship than upon the design.

Table III gives the results obtained by grouping the plugs according to the insulating material used. The good performance of glass plugs is due to their being of molded construction. The difference between porcelain and mica is too slight to be given much weight; but indicates that the laminated structure of the mica does not seriously decrease its gas tightness. This result is confirmed by a second set of averages, including only high-grade plugs which are actually used to a considerable extent on aviation engines. The porcelain plugs showed

Grade B+ and the mica plugs Grade B. The number of plugs tested of the other materials is insufficient to support any definite conclusions.

The leakage of a spark plug is more dependent upon workmanship than upon design, since tight and leaky plugs have been found in nearly every design submitted for test.

TABLE I.

Name of plug.	Material.	Number tested.	Grade.	Name of plug.	Material.	Number tested.	Grade.
Anderson	Glass	27	A	Leda	Porcelain	9	B
A. C. F	Mica	7	C	Lodge	Mica	27	B−
Baby Reflex	Porcelain	3	C	Mosler	do	3	B+
Bakelite	Bakelite	6	D	Mosler Vesuvius	do	7	C
Barnes & Hawkins	Porcelain	1	B+	Mosler	Porcelain	11	A
Baysdorfer Affinity	do	6	B−	Oleo	Mica	12	B
Benton	do	6	C	O. L. M	do	6	C
Berkshire	do	6	B	Pittsfield	do	1	B+
Do	Mica	6	C	Pognon	Porcelain and mica	6	B
Bethlehem	do	12	A−	Pola	Mica	6	D
Do	Porcelain	21	A−	Randall	Porcelain	3	C
Bosch	Steatite	6	D	Rajah	do	10	B
Bugatti	Porcelain	4	C	Rajah Pasha	do	12	C
Comet	Mica	5	C	Rajah Frenchtown	do	4	B+
Champion	Porcelain	28	B	Red Head	Vitristone	2	C
Conill	Mica	3	A	Renault	Mica	9	D
Duffy Air Line	Porcelain	5	B	Ré V	Porcelain	9	A−
Duffy Quartz	Quartz and mica	12	A	Siebert	Quartz and Condensite	1	B+
Duffy Express	Porcelain	4	B	Splitdorf	Mica	39	B
Fert	do	18	A−	Stewart V Ray	Porcelain	6	D
Gnome	Mica	6	C	Sullivan	Mica	6	B
Hercules	Porcelain	9	D	Sharp Motor Cycle	do	6	D
Herz. Bougie	Steatite	20	B	Sharp Mica	do	6	D
Johns-Manville	Porcelain	3	B	Sharp Ponsot	do	2	D
Joly	do	6	B+	Titan A. C	Porcelain	33	B+

TABLE II.

Method.	Plugs tested.	Average grade.	Method.	Plugs tested.	Average grade.
Screw bushing	300	B	Spun gland	21	A−
Molded, glass	27	A	Crimped	79	B
Taper fit	32	B	Molded (organic materials)	7	C

Average=4.2, or Grade B.

TABLE III.

Material.	Number plugs tested.	Average grade.	Material.	Number plugs tested.	Average grade.
Porcelain	245	B	Quartz mica	12	A
Mica	169	B−	Porcelain and mica	6	B
Glass	27	A	Quartz and Condensite	1	B+
Bakelite	6	D			

Average=3.8, or Grade B.

REPORT No. 51.

PART III.

METHODS FOR TESTING SPARK PLUGS.

By H. C. Dickinson, F. B. Silsbee, and P. G. Agnew.

RÉSUMÉ.

The factors which affect the performance of spark plugs in gasoline engines are very numerous, subject to erratic variation, and differ widely with the type of engine. Consequently definite conclusions as to the ultimate value of a given type of plug can be based only on reliable statistical data on the performance of a large number of plugs. An engine test of a few hours' duration serves to develop any marked weakness in a spark plug and is the most valuable over all test. Laboratory tests determine quantitatively certain specific properties of a spark plug rapidly and conveniently, and have three chief functions. These are (1) the indication of probable weak points in new designs of plugs, (2) the indication of progress in the development of improvements or the elimination of faults in design or material, and (3) a check on production by means of routine tests. The tests described below have been developed at the Bureau of Standards for these purposes.

The first test is for the electrical conductivity of the insulating material while hot. The specimen to be tested is heated in an electric furnace to the desired temperature and the resistance measured, using 60-cycle alternating current at 500 volts. The conductivity of this class of materials is found to vary very rapidly with the temperature, approximately obeying a law of compound interest with an increase of 2 per cent per degree Centigrade. The quality of the material is therefore very conveniently expressed by stating the temperature (T_e) at which it has an arbitrarily selected resistivity. This value has been selected as one megohm per centimeter cube, and a spark plug of the usual construction, made of material of this resistivity, will have a resistance of about 200,000 ohms. This is slightly on the safe side of the limit at which the usual forms of ignition system may be relied upon to give regular firing in a high compression motor.

The following table gives some typical results obtained by this method:

	c.	b.	T_e.	ρ 500.
Quartz	11.8	0.0065	890	340 x 10^6
Best porcelain tested	11.2	.0066	790	80
Typical mica plug	12.1	.0085	720	70
Average of three aviation porcelains	11.5	.0085	650	40
Average automobile porcelain	10.2	.0085	490	0.80

The resistance of the insulating material to thermal cracking is tested by heating the specimen to 300° C. and then quenching it in water at room temperature. The sample is then soaked in an aniline dye which renders visible any cracks which may be present.

The assembled plugs are tested for gas tightness with compressed air at a pressure of 225 pounds per square inch while the plug is immersed in a bath of oil heated to 150° C. This serves to duplicate the conditions in the engine which may cause leaks due to the thermal expansion of the various parts of the plugs. The air leaking through the plug is collected in a glass tube and measured.

The resistance of the plugs to breakage by mechanical shock is tested by screwing the assembled plug into the side of a steel block which, by a trip hammer arrangement, is struck repeatedly against a hardened steel rail. The number of impacts delivered before the plug is damaged is taken as a measure of its performance.

The cold dielectric strength test is made by applying 60-cycle voltage from a transformer to the plug insulator while it is immersed in a vessel of oil. The voltage is raised gradually to 25,000 volts and any puncture of the material is considered a failure.

The engine test consists in running the plugs in a high compression aviation engine at full load for six hours and at light load for one hour, and noting the general performance of the plugs.

INTRODUCTION.

The methods of test described in this report have been developed at the Bureau of Standards as a part of the investigation of ignition problems. The object of laboratory tests of this nature is to determine certain specific properties of the material or design of the plug under conveniently controllable conditions, both for the purpose of developing improvements in certain particular properties and for comparing the relative merits of different types of plug in regard to these properties, thus permitting the elimination of types notably inferior in any important characteristic. The engine test serves to bring out any other source of weakness and indicates the general utility of the plug. It should be emphasized that prolonged running in an engine of the type in which the plugs are to be used is the only ultimate basis for judging the merits of a given type.

The tests employed are as follows:

1. Test for electrical conductivity of insulating material.
2. Test for resistance of insulator to thermal cracking.
3. Test for gas tightness.
4. Test for resistance to mechanical vibration.
5. Test for dielectric strength.
6. Engine test.

These tests are necessarily in continual process of development, and the directions given below are subject to frequent revision.

ELECTRICAL CONDUCTIVITY.

The measurement of electrical conductivity is made either on spark plug insulators or on specially designed test specimens. In either case the sample of insulating material to be tested is heated in an electric furnace to the desired temperature and 60 cycle alternating current at 500 volts is then impressed upon the specimen between two suitable electrodes. A voltmeter connected between these electrodes and an ammeter in series with the specimen are read simultaneously and the resistance is taken as the quotient of effective voltage divided by effective current.

Since the current through the specimen is rather small, a very sensitive milliammeter is required and it is usually found convenient to use for this purpose a dynamometer wattmeter. The fixed coil of this wattmeter is excited by a known current from the same source of supply as the test current through the specimen. The moving coil of the wattmeter is connected in series with the specimen. Such an arrangement provides a higher sensitivity than can be attained with commercial milliammeters, and is also convenient because of the great range of currents which can be measured by using various exciting currents. The connections used in this test are shown in figure 1.

Measurements made by this method on the same sample are found to give results agreeing to a few per cent when different voltages, frequencies, and times of application of the measuring current are used.

For the accurate measurements of the conductivity of the material, a cup specimen, similar to the American Society for Testing Materials' standard test piece No. 1, should be used, though it is not essential that the side walls of the cup be tapered. Figure 2 gives a cross-section of

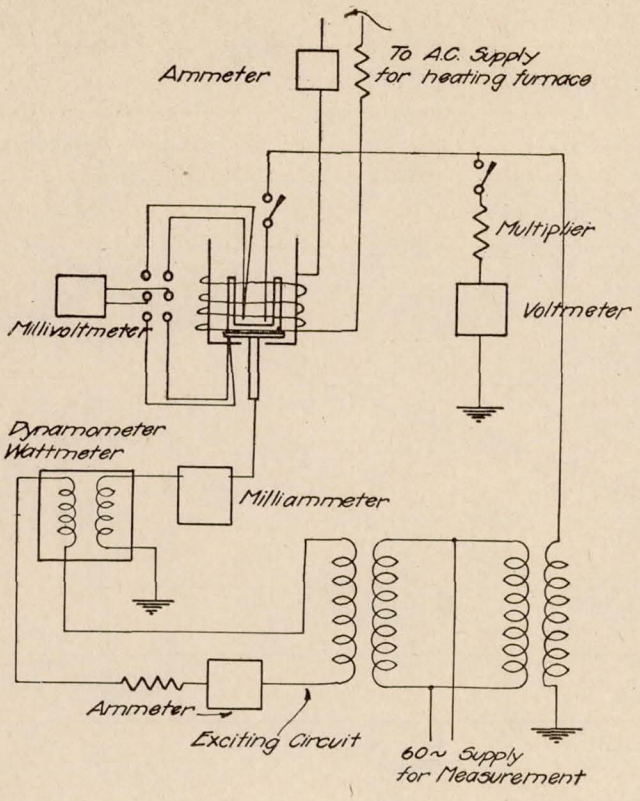


FIGURE 1.

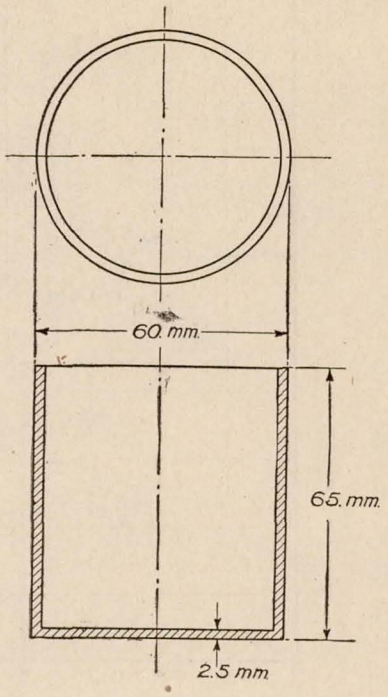


FIGURE 2.
PORCELAIN TEST SPECIMEN.

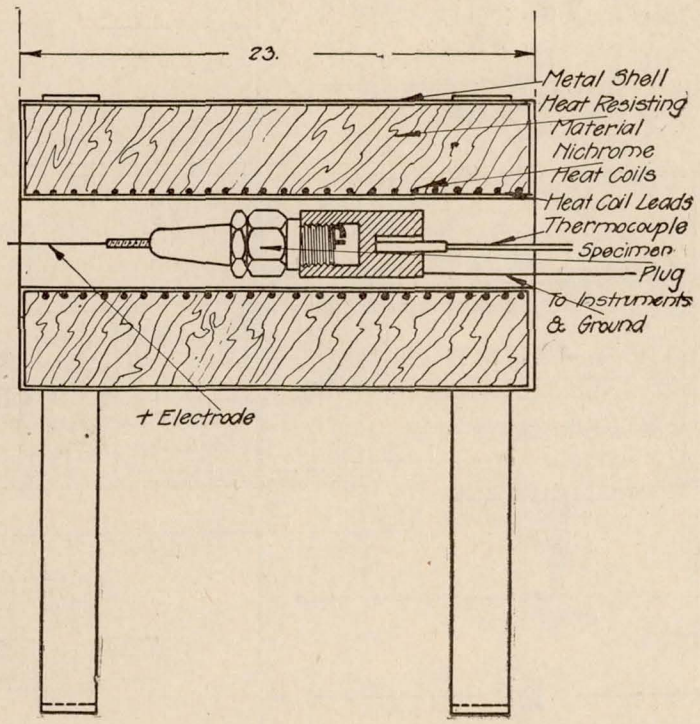


FIGURE 4.

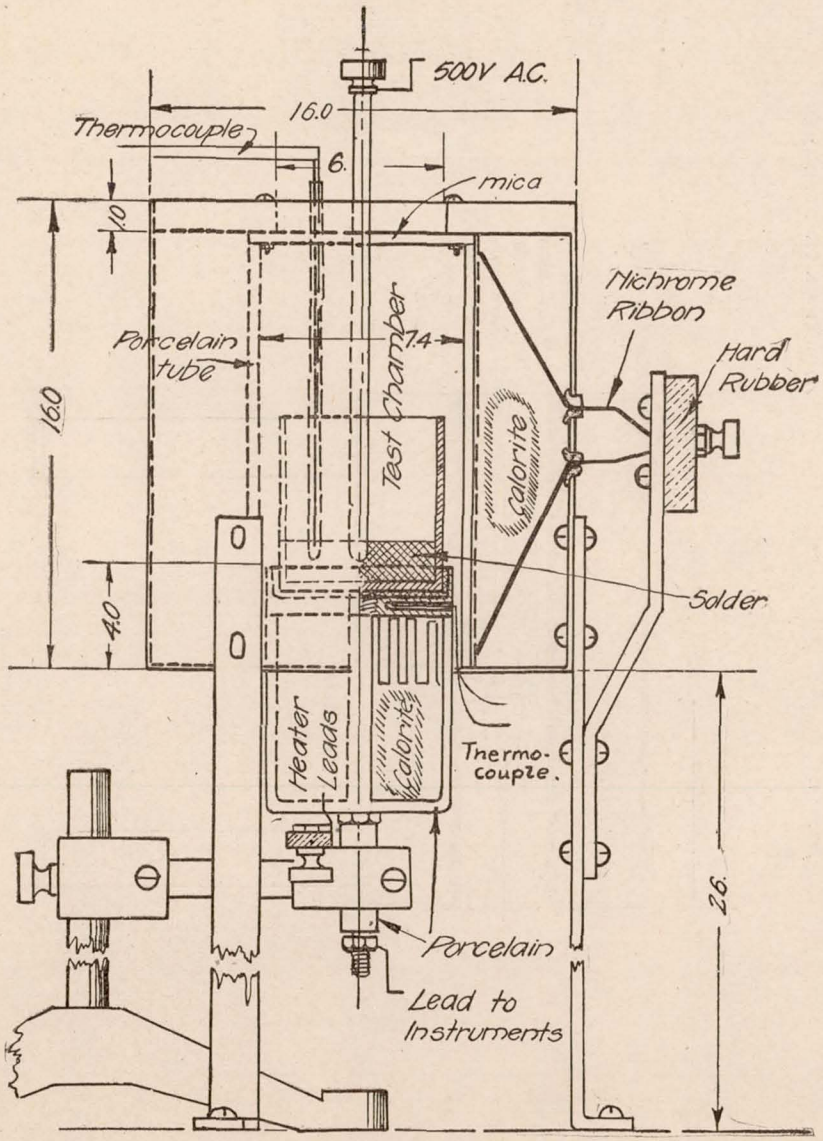
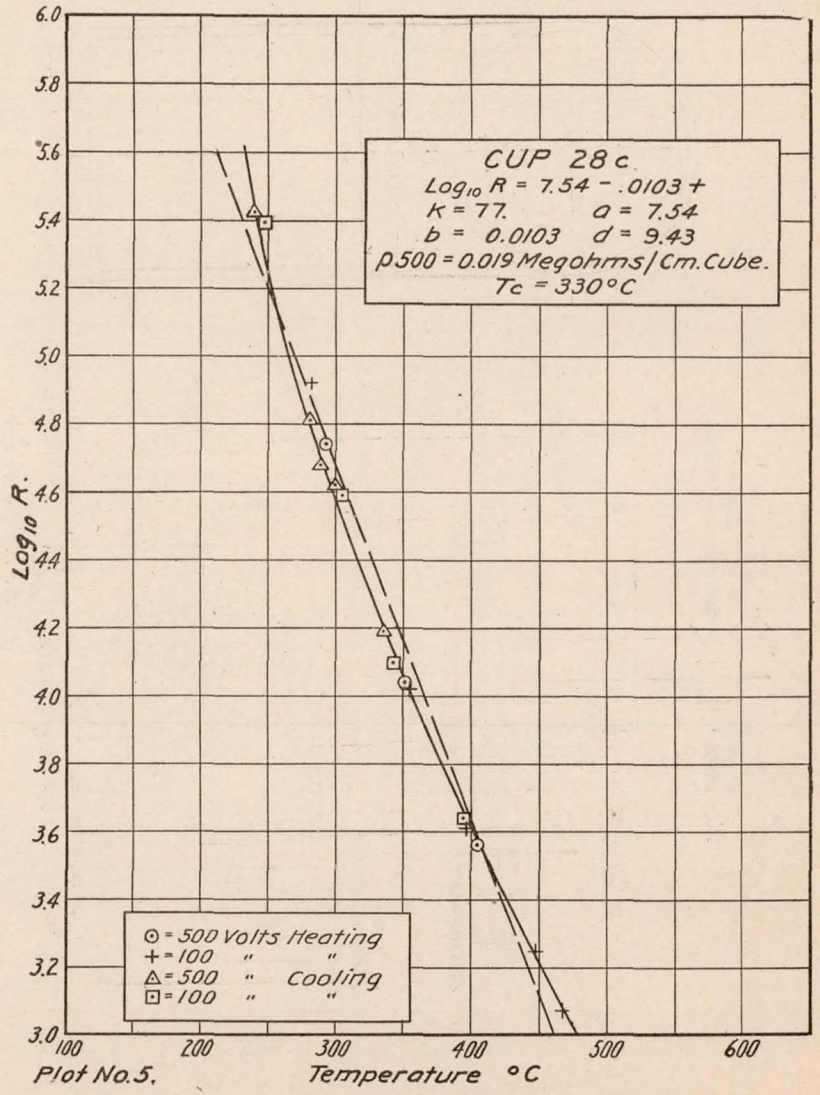

500V A.C.
16.0
Thermocouple
6.
mica
1.0
Porcelain tube
7.4
Test Chamber
Nichrome Ribbon
Hard Rubber
Calorite
16.0
Solder
4.0
Heater Leads
Calorite
Thermo-couple.
26.
Porcelain
Lead to Instruments

FIGURE 3.


CUP 28c
Log10 R = 7.54 - .0103 +
K = 77. a = 7.54
b = 0.0103 d = 9.43
ρ500 = 0.019 Megohms/Cm. Cube.
Tc = 330°C
⊙ = 500 Volts Heating
+ = 100 " "
△ = 500 " Cooling
⊡ = 100 " "
Log10 R.
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
100
200
300
400
500
600
Temperature °C
Plot No.5.

this type of specimen. The resistivity of the material can be computed by multiplying the desired resistance of such a cup by the factor K obtained from the equation $K=\frac{\pi d^2}{4t}$ where d is the diameter of the cup and t the thickness of the bottom.

This test cup is filled to a depth of about 2 cm. (0.8 inch) with melted solder, which forms one electrode, and is in turn set in a slightly larger shallow steel cup containing melted solder, which forms the other electrode. This arrangement insures good contact between the electrodes and the porcelain. To avoid cracking the cup, it is, of course, necessary to insert the solder in the solid form and melt it by gradually increasing the furnace temperature. Figure 3 shows the arrangement of the cup specimen in the furnace. Two thermocouples protected by porcelain tubes are inserted in the solder in the test specimen and in a hole in the steel cup respectively. Measurements of resistivity are made only when these two couples indicate substantially the same temperature.

In cases where cup specimens are not available, actual spark-plug insulators can be tested by using the central electrode as one terminal and the shell of the spark plug as the other. If the insulator is removed from the shell, a band about 2 cm. (0.8 inch) wide at the center of the length of the insulator is coated with platinum by applying a layer of platinum chloride solution and then heating this to reduce the chloride and leave a deposit of metallic platinum. This platinum belt is then used as the outer terminal. The specimen is inserted in an electric furnace, as shown in figure 4, the temperature of which is indicated by a thermocouple placed in contact with the shell of the plug.

Measurements obtained on these specimens are accurate as indicating the resistance of the specimen, but owing to the irregular shape and the uncertainty as to the area of outer electrode in actual contact with the porcelain they are not suitable for accurately measuring the resistivity of the material. Assuming the usual formula for current flow between coaxial cylinders, the factor K by which the resistance must be multiplied to give the resistivity of the material can be computed by the equation

$$K=\frac{2\pi L}{2.3 \log_{10} \frac{d_1}{d_2}},$$

where L is the effective axial length of the electrode, and d_2 and d_1 are the diameters of the inner and outer electrodes. In this computation, it is assumed that the contact is made over the entire surface covered by the shell of the plug, and consequently the values of resistivity computed on this basis are too high if this contact is imperfect. It should also be noted that the path for surface leakage is much shorter in the case of the plug specimen, and also that if the glaze is of poorer material than the body of the plug, conduction through this glaze will reduce the apparent resistivity. In the cup specimen, on the other hand, the area of contact and thickness of the bottom of the cup are definite and easily measured. It is found that in general measurements on plug samples give lower resistivity than those on cups.

The change of resistivity with temperature in this class of materials is so rapid that it is impracticable to plot resistivity against temperature directly, as a scale which is suitable at one end of the temperature range becomes extremely crowded at the other. It is found, however, that by plotting the logarithm of the resistivity against the temperature, a smooth curve slightly concave upward is obtained. The curvature of this plot is quite small and the data can be represented within the range of temperature used with sufficient accuracy by a straight line which more nearly fits the observed points. Plot 5 shows a typical plot of data obtained on a cup sample.

The points on the straight line give the relation

$$\text{Log}_{10} R=a-bt$$

where R is the resistance of the specimen in ohms and t the temperature in degrees Centigrade, while a and b are constants of the curve. Adding log K to both sides of this equation we obtain

$$\text{Log}_{10} \rho=a+\log_{10} K-bt=c-bt$$

where ρ is the resistivity in ohms per centimeter cube and c a new constant of the material which is obtained from a by the equation

$$c = a + \log_{10} K.$$

The constants c and b depend upon the material only and not upon the shape or size of the particular specimen, and from a knowledge of these constants ρ can be computed for any temperature by the above equation. Unfortunately neither c nor b is very convenient as a figure of merit for the material, since a slight error in either will greatly affect the value of the other. It is, therefore, advantageous to compute for each material $\rho 500$ which is the resistivity of the material at 500° C. Another very convenient figure of merit is the temperature at which the material has a definite resistivity of 1 megohm per centimeter cube. This can be computed by the equation

$$T_e = \frac{c-6}{b}.$$

This value is given in the reports of this bureau for each material tested and is the most satisfactory criterion of its value as an insulator at high temperature.

An interpretation of the fact that the results as thus plotted give a straight line can be obtained by considering that the conductivity increases with temperature according to the law of compound interest, at a rate of about 2 per cent per degree Centigrade. This rate is equal to $2.3 \times b$ for each material. The cumulative effect of the compounding is such that an increase in temperature of 100° corresponds in the average material to an increase of the conductivity by 600 per cent.

The following table gives some typical results obtained by this method:

	c.	b.	T_e.	ρ_{500}.
Quartz	11.8	0.0065	890	340 x 10^6
Best porcelain tested	11.2	.0066	790	80
Typical mica plug	12.1	.0085	720	70
Average of three aviation porcelains	11.5	.0085	650	40
Average automobile porcelain	10.2	.0085	490	0.80

A material having T_e less than 400° C. should not be used unless the design of the plug is such as to keep the insulator well cooled. An assembled plug having less than 0.5 megohm resistance at 400° C. should be considered unsatisfactory.

RESISTANCE TO THERMAL CRACKING.

The quenching test is intended to indicate the ability of the insulating material to resist cracking due to steep temperature gradients. The insulators with the shell and central electrode removed are brought to a uniform temperature of 300° C. in a small furnace and then quenched in water at room temperature and examined for cracks by soaking for several hours in an alcoholic solution of the dye eosin. The specimen is then broken to determine the depth of the cracks. The cracks developed by this test seldom extend entirely through the specimen so that an electrical test is not as satisfactory for indicating them as is the use of the penetrating stain. Practically all insulators will show some cracks when quenched from 300° C. but the number and depth of the cracks varies very greatly among different specimens and the test gives a qualitative basis for the comparison of different materials.

TEST FOR GAS TIGHTNESS.

Gas tightness is determined by screwing the completed plugs into a steel bomb and admitting air at a pressure of 225 pounds per square inch to the interior. By the use of lead washers in place of the usual copper-asbestos gaskets a tight joint can be secured between the plug and the bomb. The entire bomb is then immersed in a tank of oil which serves to show the leakage by the resulting bubbles. The oil is heated to 150° C. and consequently heats the plugs and develops leaks which may arise under operating conditions due to the differential thermal expansion of different parts of the plug. The actual amount of gas leaking out is measured

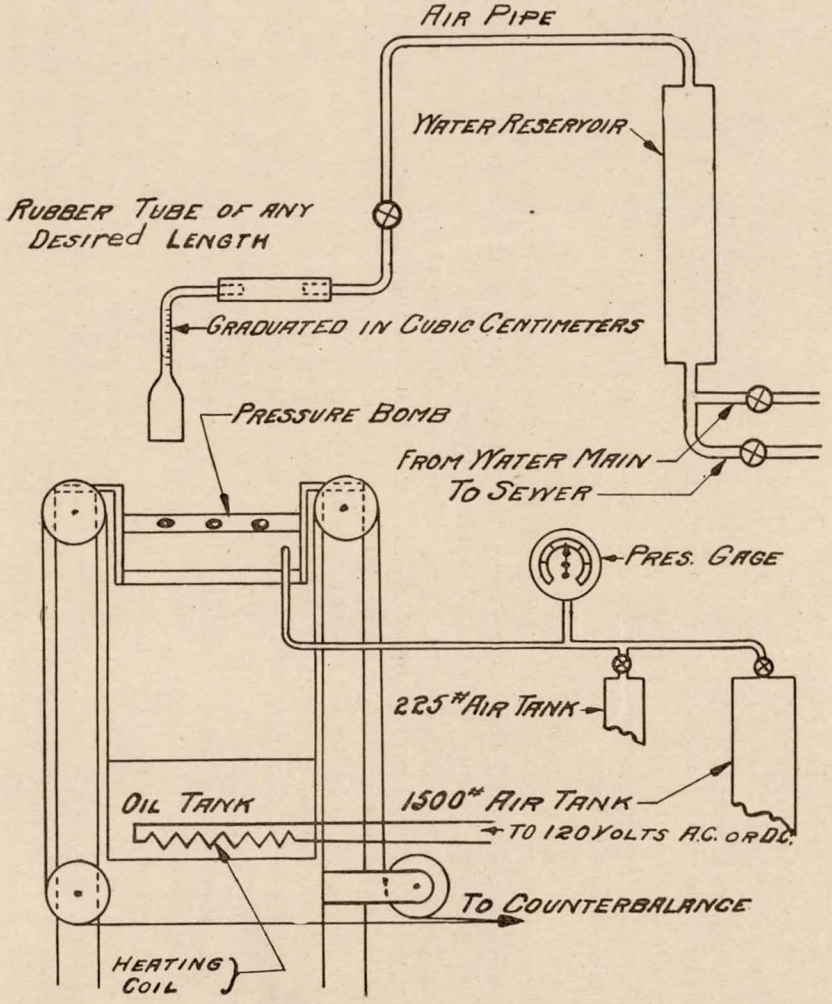
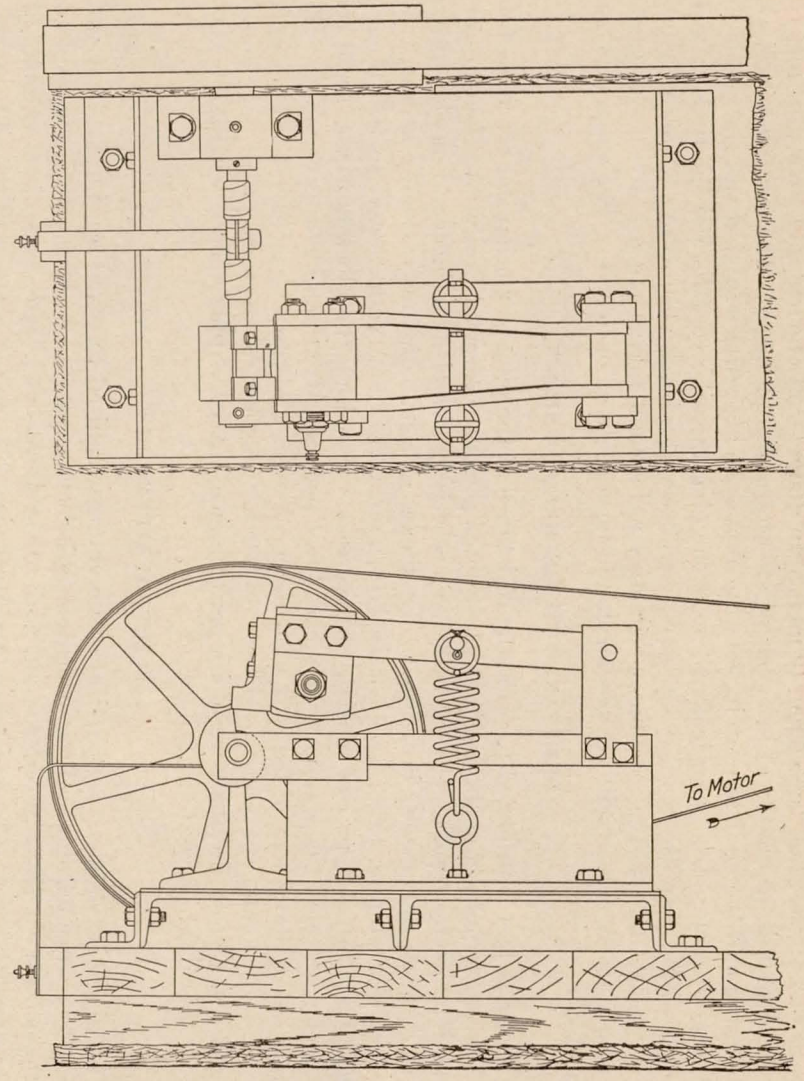


FIGURE 6.



SCHEME OF IMPACT TESTING MACHINE.

FIGURE 7.

by means of a Pyrex glass tube 5 cm. (2 inches) in diameter at one end and 1 cm. (0.4 inch) at the other, which is graduated at intervals of about 5 mm. (0.2 inch). The large end is slipped over the plug and the oil drawn up in the tube above the highest graduation and the upper end of the tube then closed. As air leaks through the plug the oil level falls and the time required for it to fall between two calibrated marks is observed with a stop watch. This gives, by division, the actual leakage in cubic centimeters per second taking place. A leakage greater than 0.2 c. c. (0.01 cubic inch) per second should be considered excessive. The apparatus used is indicated in figure 6.

RESISTANCE TO MECHANICAL SHOCK.

The shock test is intended to show the resistance of the plug to mechanical breakage from the shock and vibration of the engine. Completed plugs are screwed firmly into the sides of a steel block 6 by 6 by 9 cm. (2.4 by 2.4 by 3.5 inches) which is carried on the end of an arm 24 cm. (9.5 inches) long as sketched in figure 7. By means of a pair of cams revolving at about 300 revolutions per minute, this block is raised 19. mm. (0.75 inch) and allowed to fall upon a hardened steel rail. A pair of tension springs assists in pulling the block downward and give it a velocity of about 200 cm. per second (6.7 feet per second) at the instant of impact. The total number of blows is recorded by a counting mechanism and the plug is inspected at frequent intervals. The number of impacts delivered before the plug is cracked or otherwise mechanically damaged is taken as the measure of its performance. A good plug should withstand 25,000 blows in this machine without failure.

DIELECTRIC STRENGTH.

The dielectric strength test indicates the voltage required to puncture the insulator while cold and has proved useful in eliminating poor or defective insulators. It is applied to insulators with the central electrode in position but with the shell removed. One secondary terminal of a step-up transformer is connected to the central electrode and the other terminal to a metal band approximately 10 mm. (0.4 inch) wide wrapped around the outside of the insulator. The whole is then immersed in oil at room temperature. Alternating voltage of commercial frequency is applied to the primary of the transformer and gradually increased until an effective voltage of 25,000 is reached. The insulation should withstand this voltage for two minutes without puncture. In short insulators a spark may pass over the surface of the insulator through the oil at voltages somewhat below 25,000. Such flashovers may sometimes be avoided by carefully rinsing the surface of the insulator with gasoline, and in any event should not be considered as a failure.

ENGINE TEST.

Spark plugs intended for use in a particular type of engine should, if possible, be tested in an engine of this same type. For general testing, the plugs are run in a modern aviation engine having a ratio of total cylinder volume to clearance volume not less than 5.3 to 1, preferably driving a propeller or a club. The engine is run at full power for a total period of six hours with not more than three interruptions, and is then run one hour throttled down to about 400 revolutions per minute. If the engine has two plugs per cylinder, either the plugs to be tested are put in both sides or, if the number of samples is insufficient, the plugs are moved in the middle of the test so as to be run for about half the time in each location. The temperature of the cooling water leaving the engine is maintained between 65° C. and 70° C. (149° to 158° F.). The temperatures of the oil in the crank case, of the cooling water, and of the surrounding air are recorded, together with the average power developed and the oil and fuel consumption. At intervals, each ignition system is cut off to indicate missing in the other set of plugs, and any misfiring or preignition due to the plugs is noted. The plugs are examined at the end of the run to determine if any corrosion or warping of the electrodes, as shown by a change in the length of the gap, fouling with carbon, cracking of the insulator, or other defect occurred. The plugs are also subjected to the test for gas tightness both before and after the engine tests, and if cracking of the porcelain is suspected the insulators are removed from the shells and soaked in an alcoholic solution of eosin to indicate any cracks which may exist.

REPORT No. 52

TEMPERATURES IN SPARK PLUGS HAVING STEEL AND BRASS SHELLS

BY

C. S. CRAGOE

Bureau of Standards, Washington, D. C.

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REPORT No. 52.

TEMPERATURES IN SPARK PLUGS HAVING STEEL AND BRASS SHELLS.[1]

By C. S. Cragoe.

RÉSUMÉ.

This investigation was conducted at the Bureau of Standards for the National Advisory Committee for Aeronautics.

Brass has often been assumed superior to steel for spark plug shells because of its greater heat conductivity. The measurements described in this report prove the contrary, showing that the interior of a spark plug having a brass shell is from 50° to 150° C. (90° to 270° F.) hotter than that of a similar steel plug. Consistent results were obtained in both an aviation and a truck engine, and under conditions which eliminated all other sources of difference between the plugs. It is to be concluded that steel is to be preferred to brass for spark plug sh lls.

INTRODUCTION.

The measurements described below were undertaken to compare the temperatures attained in various portions of spark plugs having brass and steel shells. The plugs used were of the Rajah type. The porcelains were especially made with a hollow central (electrode) space of approximately 2 mm. (0.08 inch) diameter and sealed at the lower end. The temperature gradient along this central axis of the porcelain was measured with a movable copper constantan thermocouple. A brass tube about 2 cm. (0.8 inch) in diameter and 15 cm. (6 inches) in length was attached to the upper part of the shell of each plug to protect the thermocouple and to support it in any desired position.

MEASUREMENTS WITH PLUGS IN HALL-SCOTT MOTOR.

Two plugs with brass and two with steel shells were placed in the regular spark plug holes on the exhaust side of a four-cylinder Hall-Scott motor, type A–5a, running at a speed of about 1,500 revolutions per minute, and delivering about 110 horsepower to an airplane propeller. A separate run was made for each plug and the temperatures measured after sufficient time had elapsed (about a half hour) for the temperature to become constant. The temperature of the discharge water from the cylinders was about 70° C. (158° F.) in each case. The following table contains the results of the measurements. The first column gives the position of the thermocouple from the bottom of the porcelain. This was limited by the depth of the central space.

Table I.

Position.		Temperatures °C. in aviation engine.					
		In cylinder I.		In cylinder II.		In cylinder I.	
Cm.	Inches.	Brass A.	Steel A.	Brass A.	Steel A.	Brass B.	Steel B.
1.5	0.59	.....	.....	.....	.....	435	325
2.0	.79	380	220	375	225	395	290
2.5	.98	355	180	360	210	350	260
3.0	1.18	310	155	330	180	305	225
3.5	1.38	255	130	285	155	265	195
4.0	1.57	200	120	215	125	210	160

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 12.

These values are shown in plot 1.

The gas leakage on the above plugs was measured at 225 pounds pressure and 150° C. with the following results:

	Brass.	Steel.
A	0.01 cc. per sec	0.05 cc. per sec.
B	0.36 cc. per sec	0.45 cc. per sec.

The pitch diameters of the threads (in inches) were measured by choosing the two central threads and taking diameters at right angles.

Brass.		Steel.	
A.	B.	A.	B.
0.6680	0.6696	0.6663	0.6707
.6682	.6688	.6642	.6692
.6672	.6678	.6640	.6668
.6675	.6680	.6637	.6665
Mean . .6677	.6685	.6645	.6683

MEASUREMENTS IN A TRUCK MOTOR.

Similar measurements were made in a Waukesha truck motor with special cylinder heads which gave a maximum compression of about 115 pounds per square inch. This motor was connected with a dynamometer and loaded down with the throttle wide open to run at a speed of 1,000 revolutions per minute. There was no fan or radiator connected but the discharge water was thermostated at a temperature of 63° C. (145° F.). Each plug was placed separately in the second cylinder and in the same spark plug hole, which was specially drilled and tapped in a position originally used for a priming cup. The bottom of the plugs lacked about 2.5 cm. (1 inch) of being flush with the inside cylinder wall. The temperature gradients along the central axis of the porcelains were measured as before. An additional thermocouple was placed about 2 mm. (0.08 inch) within the metal of the shell of each plug and level with the copper gasket below the shoulder of the porcelain.

TABLE II.

Position (from bottom of porcelain).		Temperatures °C. in truck engine.					
Cm.	In.	Brass A.	Steel C.	Brass C.	Steel D.	Brass A.	Steel C.
2.0	0.79	227	158	245	173	230	156
2.5	.98	169	133	173	141	171	135
3.0	1.18	147	120	149	125	149	120
3.5	1.38	135	111	135	114	137	116
4.0	1.57	128	104	126	108	130	108
4.5	1.77	121	100	121	103	123	101
Thermocouple in shell..		135	112	135	116	.....	.....

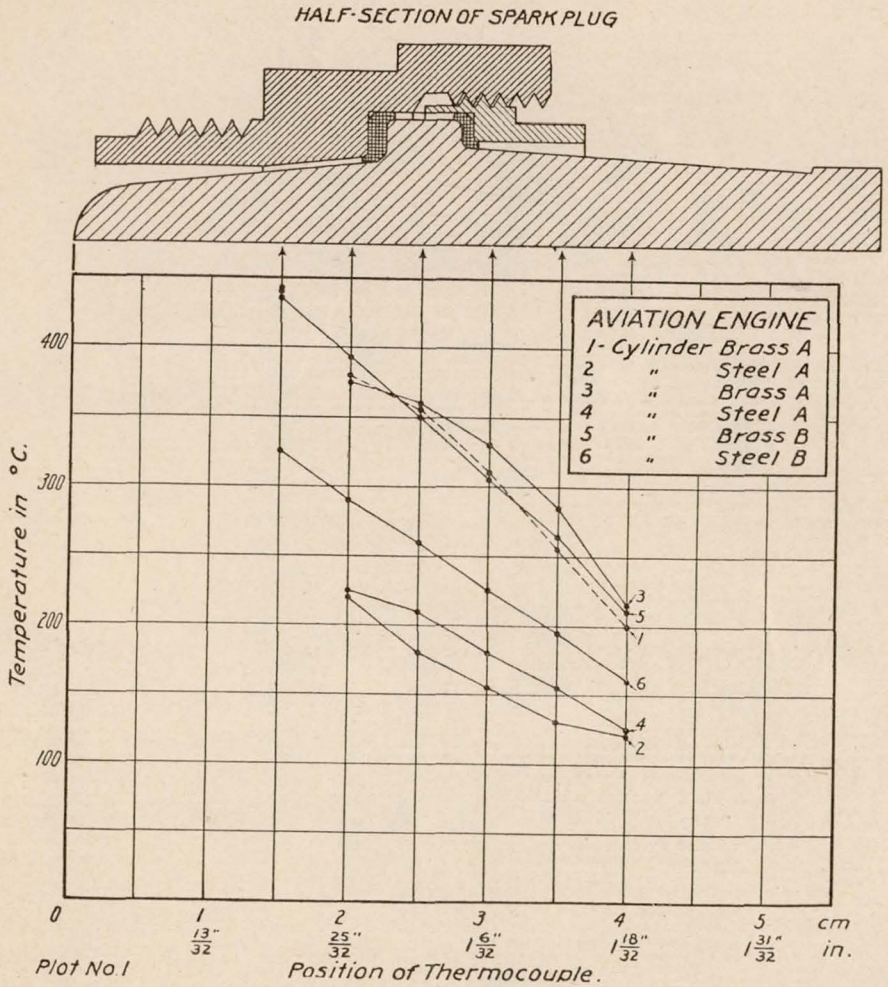
These values are shown in plot 2.

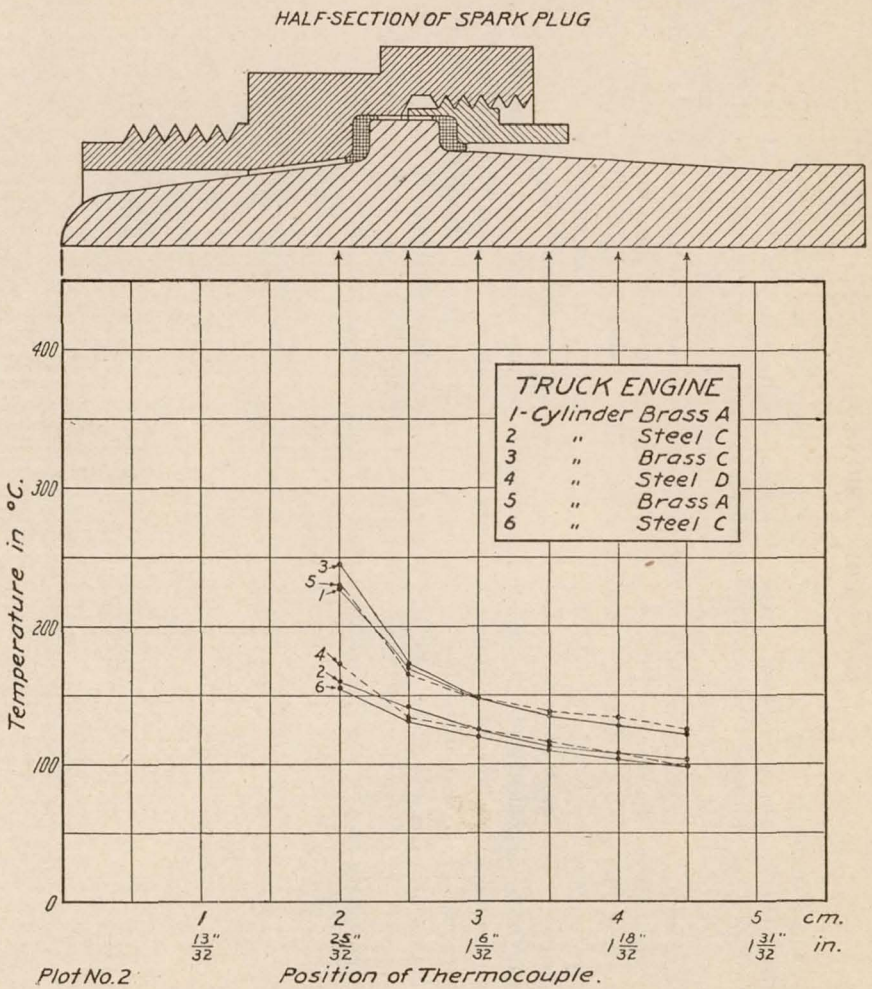
The gas leakage was carefully measured at 220 pounds pressure and 155° C. and plugs purposely chosen having wide variations.

	Brass.		Steel.
A	0.009 cc. per sec.	C	0.03 cc. per sec.
C	1.5 cc. per sec.	D	1.6 cc. per sec.

The pitch diameters of the threads in inches were:

Brass.		Steel.	
A.	C.	C.	D.
0.6680	0.6697	0.6692	0.6668
.6682	.6686	.6684	.6668
.6672	.6676	.6674	.6659
.6675	.6678	.6670	.6661
Mean .6677	.6684	.6681	.6664


HALF-SECTION OF SPARK PLUG
AVIATION ENGINE
1- Cylinder Brass A
2 " Steel A
3 " Brass A
4 " Steel A
5 " Brass B
6 " Steel B
Temperature in °C.
400
300
200
100
0
1 13/32" 2 25/32" 3 1 6/32" 4 1 18/32" 5 1 31/32" cm in.
Position of Thermocouple.
Plot No. 1


HALF-SECTION OF SPARK PLUG
TRUCK ENGINE
1- Cylinder Brass A
2 " Steel C
3 " Brass C
4 " Steel D
5 " Brass A
6 " Steel C
Temperature in °C.
400
300
200
100
0
1 13/32" 2 25/32" 3 1 6/32" 4 1 18/32" 5 1 31/32" cm. in.
Position of Thermocouple.
Plot No. 2

CONCLUSIONS.

The measurements indicate that the temperatures of the brass shells are considerably higher than the steel in each case. Also, the temperatures in the center of the porcelain are higher in the case of brass shells. This difference can not be attributed to difference in gas leakage, since plugs of the same material differing quite widely in leakage gave practically identical results. Also, the thread dimensions were so nearly the same that the difference in temperature can not be due to difference in the contact between the plug and the jacket, and is apparently due to the difference in the material of the shell. This effect is apparently due to the greater thermal conductivity of brass (0.22 c. g. s. units) as compared with steel (0.11 c. g. s. units). The heat received from the hot gases in the cylinder by the inner end of the brass plug is more readily conducted longitudinally to the upper part of the shell, which is thus maintained at a relatively higher temperature in spite of the loss of heat from the upper portions of the shell and insulator by radiation and convection. Since the contact between the porcelain and the plug is above the plane of the engine water jacket, the porcelain is less effectively cooled in the case of the brass plug where the upper part of the metal is hotter, and consequently shows a higher temperature throughout its length.

REPORT No. 53

PROPERTIES AND PREPARATION OF CERAMIC INSULATORS FOR SPARK PLUGS

Part I.—METHODS OF MEASURING RESISTANCE OF INSULATORS AT HIGH TEMPERATURES

By F. B. SILSBEE and R. K. HONAMAN

Part II.—ELECTRICAL RESISTANCE OF VARIOUS INSULATING MATERIALS AT HIGH TEMPERATURES

By R. K. HONAMAN and E. L. FONSECA

Part III.—PREPARATION AND COMPOSITION OF CERAMIC BODIES FOR SPARK-PLUG INSULATORS

By A. V. BLEININGER

Part IV.—CEMENTS FOR SPARK-PLUG ELECTRODES

By H. F. STALEY

Bureau of Standards, Washington, D. C.

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REPORT No. 53.

PART I.

METHODS OF MEASURING RESISTANCE OF INSULATORS AT HIGH TEMPERATURES.[1]

By F. B. Silsbee and R. K. Honaman.

RÉSUMÉ.

This report describes in some detail the preliminary experiments which were made on the conductivity of spark-plug insulators in order to develop a satisfactory comparative method for testing various materials. The measurements were made at temperatures between 200° and 900° C, and with both alternating and direct current at voltages as high as 2,000 volts.

The results obtained confirmed the experiments of earlier observers at lower temperatures in indicating a very rapid decrease of resistance with increase of temperature in porcelain, mica, fused silica, and similar materials. This decrease is, however, a gradual one and there is no definite temperature at which the material suddenly changes its properties. The results of conductivity measurements can be most conveniently expressed by stating the temperature (T_e) at which the material has the arbitrarily selected resistivity of one megohm per centimeter cube. Table 1 gives the values of this constant for various substances.

The measurement with direct current showed the presence of disturbing polarization effects which make the apparent resistance of the specimen vary with the magnitude and time of application of the measuring voltage. This effect can be eliminated by the use of alternating current in making the measurements and the later work on a wide variety of substances, the results of which are given in Part II of this report, was done by this latter method.

There is a wide field for further investigation of this subject, as the mechanism of conduction in this class of materials is very complex.

INTRODUCTION.

The purpose of this report is to describe some measurements carried out at the Bureau of Standards during the past two years, on the resistance of various insulating materials at high temperatures. This work was undertaken with a view to studying the relative merits of various insulators for use in spark plugs, and in particular to assist the ceramic laboratory of the bureau in developing improved porcelain bodies for this purpose. The method finally adopted as a result of this work for the comparative testing of materials is described briefly in Report No. 51, Part III, the results of a large number of measurements on a wide variety of materials are given in Report No. 53, Part II, and the development of the ceramic side of the investigation is given in Report No. 53, Part III. The present report will be confined to a description of the various phenomena observed in the experiments which led to the method finally adopted.

The electrical and thermal conditions under which a spark plug is required to operate differ considerably with the type of gasoline engine used. Measurements with embedded thermocouples have shown that the temperature of the body of the insulator within the metal shell seldom exceeds 250° C. in water-cooled engines. The tip of the inner end, however, may reach temperatures as high as 900° to 1,000° C. It therefore, appeared desirable to study the resistivity of the specimens in the range of temperature between 200° and 900° C.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 18.

The electrical stresses applied to a spark-plug insulator by the average magneto or battery coil ignition system used for firing gasoline engines are quite peculiar and difficult to duplicate in any method of measurement. The cycle of operation (see Report No. 58, Part 1) following the opening of the primary breaker contacts consists of a rapid rise of the potential applied to the spark plug from zero to a value sufficient to break down the spark gap in the engine cylinder. The break-down voltage is of the order of 6,000 volts and is reached in a few hundred thousandths of a second. After this a comparatively low voltage (800 volts) maintains the electric arc between the spark points and lasts for a few thousandths of a second. Since the interval between sparks is of the order of 0.1 second, it will be seen that the average voltage applied over a complete cycle is quite low and has been found to be approximately 150 volts. These peculiar electrical conditions should be kept in mind when considering the various methods of measurement described below.

The materials studied in this investigation included porcelains, glass, steatite, mica, and fused silica, as these constitute the only class of substances sufficiently heat resisting for use in spark plugs. While the detailed studies of polarization, etc., described in this report were made on only a few of the porcelain samples, the same effects seemed to be present to greater or less degree in all cases and the process of conduction is probably similar in all of them. The work of earlier investigators[1] has shown the complex nature of the phenomena, but as yet no complete and satisfactory theory has been worked out to account for them.

APPARATUS AND SPECIMENS.

Most of the work reported in this paper was done on cup-shaped specimens similar to the standard test piece No. 1, adopted by the A. S. T. M., except that the side walls were of uniform thickness. The cross section of this specimen is shown in figure 1. The principal advantages of this type of specimen are:

(1) The conduction takes place through the bottom of the cup, which is of definite and easily measured dimensions.
(2) The large area and small thickness of the bottom insure a relatively large current even with material of high resistivity.
(3) The path over the rim of the cup for any surface leakage is relatively long.
(4) A satisfactory contact can be made between the specimen and the electrodes by immersing the bottom of the cup in a conducting fluid (in these experiments, melted solder) and by inserting some of this fluid inside the cup to form the upper electrode.

These cup specimens were used in the furnace shown in figure 2. The heating coil inserted in the plug below the specimen was found necessary to compensate for the flow of heat through the bottom of the furnace. By proper adjustment of the relative amounts of current through the main winding and through this additional coil, the temperatures inside and outside the cup could be equalized. These temperatures were measured by two copper-constantan thermocouples, one of which was inserted in a closed porcelain tube which dipped below the surface of the solder in the interior of the cup, while the other was embedded in the steel cup containing the solder below the specimen. Readings of the resistance were taken only when these two thermocouples showed substantially equal temperatures.

In cases where cup specimens were not available, measurements were made on assembled spark plugs, and also on spark-plug insulators, and on short pieces of tubing. In these cases the conduction took place between a central electrode and either the shell of the spark plug or a band of platinum deposited around the center of the outside of the insulator or tube. The measurements with this type of specimen were definite in indicating the resistance of the specimen, but owing to the uncertainty as to the area of contact and the location of the lines of current flow it is difficult from such data to compute with accuracy the true resistivity of the material.

[1] Gray, T., Phil. Mag. ser. 5, vol. 10, p. 226, 1880.
Haworth, H. F., Proc. Roy. Soc. Lond. A 81, p. 221, 1908.
Somerville, A. A., Phys. Rev. 31, p. 261, 1910.
Campbell, Nat. Phys. Lab. 11, p. 207, 1914.
Kinnison, C. S., Proc. Am. Ceramic Soc. 17, p. 422, 1915.
Poole, H. H., Phil. Mag. 34, p. 195, 1917.
Brace, P. H., Trans. Am. Electrochem. Soc., May 5, 1918.

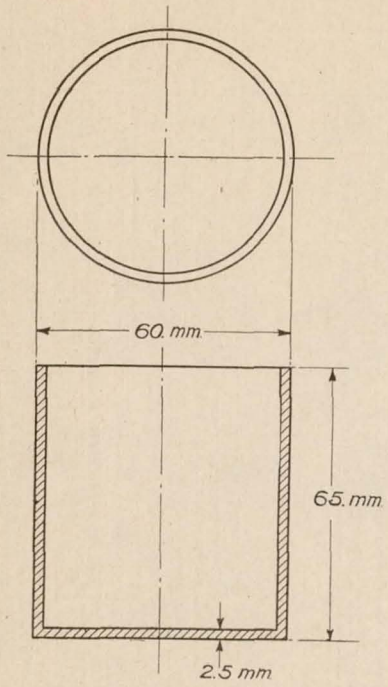


FIG. 1.—Porcelain test specimen.

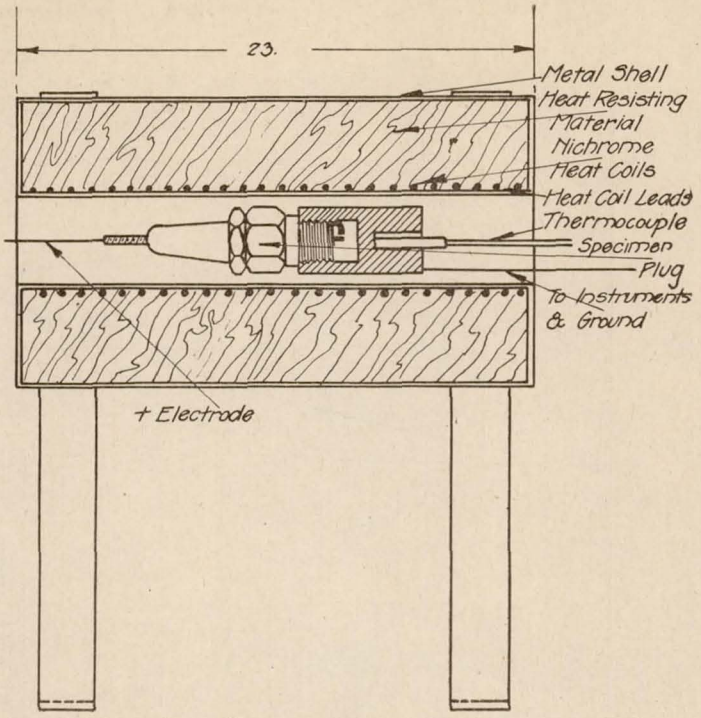


Fig. 3.

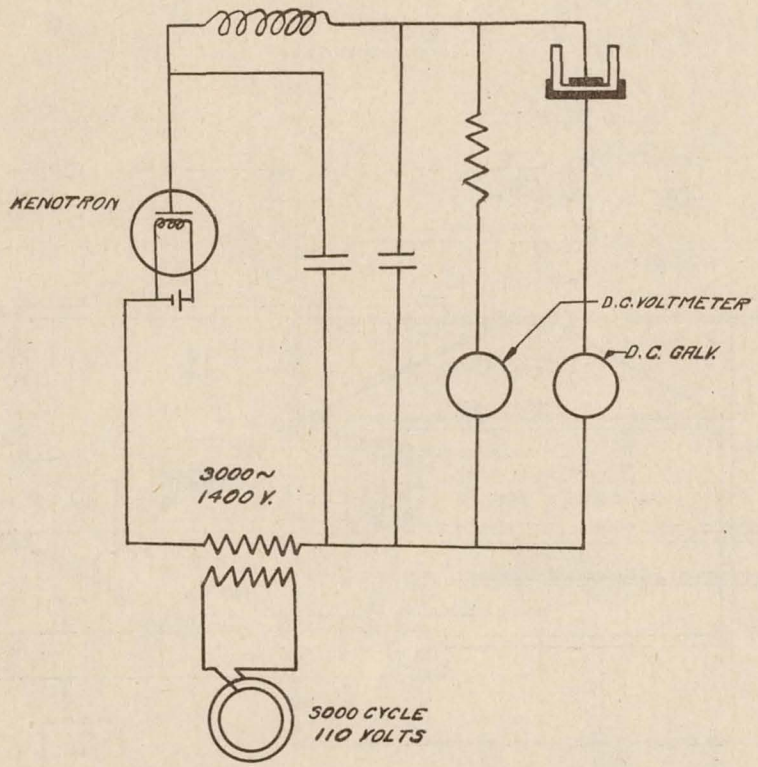


FIG. 4.—Connections for high voltage D. C. measurements.

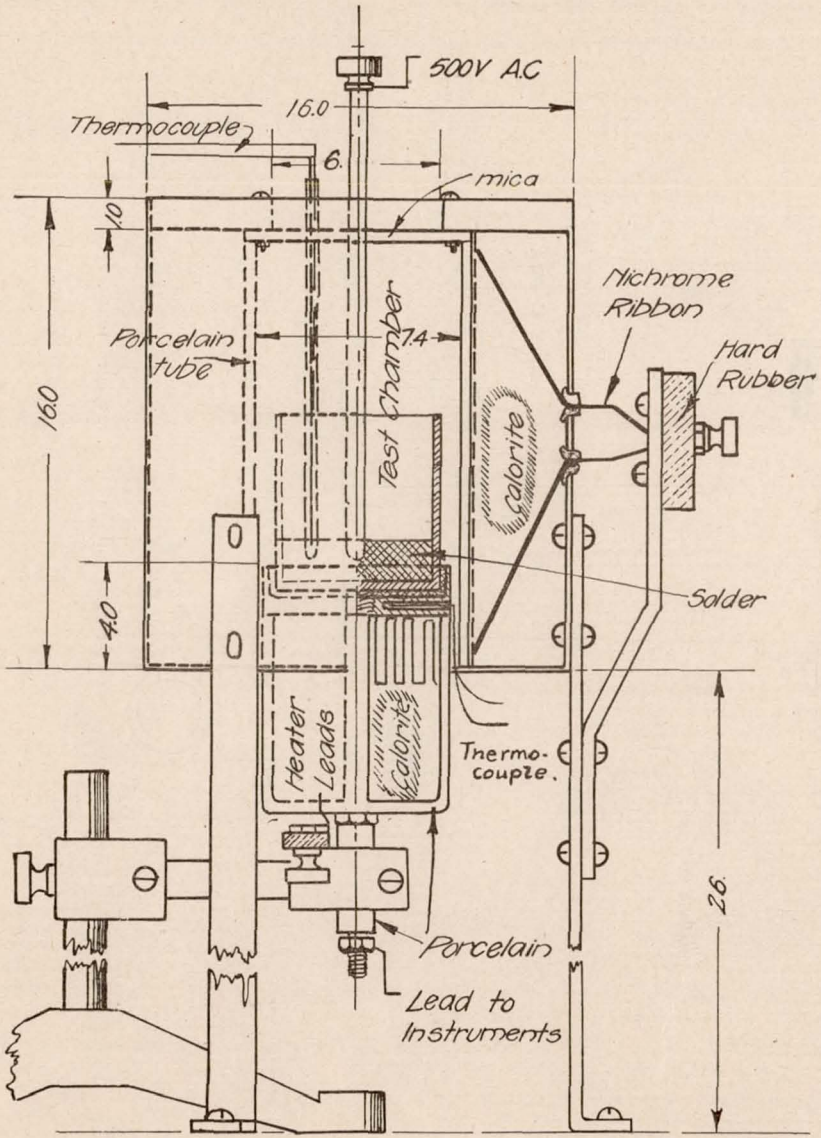
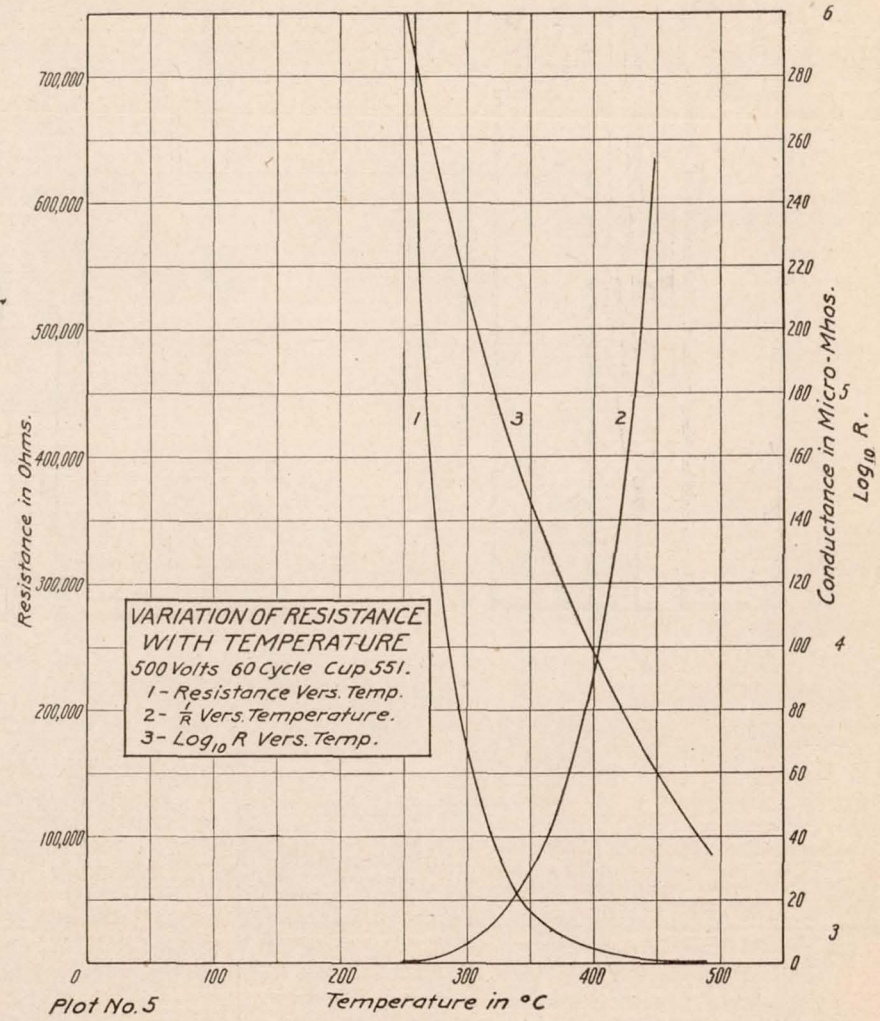

500V A.C
16.0
Thermocouple
6.
mica
1.0
Nichrome Ribbon
Hard Rubber
Porcelain tube
7.4
Test Chamber
Colorite
160
Solder
4.0
Heater Leads
Colorite
Thermo-couple.
26.
Porcelain
Lead to Instruments

FIG. 2.


VARIATION OF RESISTANCE WITH TEMPERATURE
500 Volts 60 Cycle Cup 551.
1 - Resistance Vers. Temp.
2 - 1/R Vers. Temperature.
3 - Log10 R Vers. Temp.
Resistance in Ohms.
Conductance in Micro-Mhos.
Log10 R.
Temperature in °C
Plot No. 5

For specimens of this shape the electric furnace shown in figure 3 was used, and temperatures were indicated by a single thermocouple placed in an iron plug which supported the specimen.

For reducing the results of either type of specimen from the observed resistance to a basis of the resistivity of the material the factors connecting these two quantities were computed from the dimensions of the specimens. The resistivity is obtained by multiplying the observed resistance by the factor K, where for the cup specimen

$$K=\frac{\pi d^2}{4t} \tag{1}$$

and d is the diameter of the bottom of the cup and t the thickness of the cup in centimeters. For the tubular specimen

$$K=\frac{2\pi l}{2.30 \log_{10}\frac{R_2}{R_1}} \qquad \text{(approx. 2)}$$

where l equals the length of the external conducting band measured parallel to the length of the specimen, and R_2 and R_1 are, respectively, the external and internal radii of the insulator.

In most of the work the resistances were measured by reading a voltmeter connected across the specimen and an ammeter in series with it and taking the quotient of these values as the resistance. As will be seen from the following, a wide variety of sources was used to provide the applied voltage, and the indicating instruments were correspondingly varied in character.

VARIATION OF RESISTANCE WITH TEMPERATURE.

The first experiments were carried out with an applied direct-current voltage of about 2,000 volts, which was obtained by rectifying with a kenetron a 3,000-cycle voltage supplied from a step-up transformer. The connections used to obtain this rectification and to reduce the fluctuations in the resulting continuous voltage are shown in figure 4. This rather complicated system was chosen in an attempt to duplicate to some extent the voltages existing in ignition systems, and, although this source of voltage was later abandoned, the data obtained with it brought out the salient facts in regard to this type of conduction. The most striking of these facts, as verified by other measurements made later, is the very rapid decrease in resistance of the specimen with increase in temperature. This variation amounts to aproximately 2 per cent per degree centigrade at all temperatures. If the results are expressed by plotting resistance *vs.* temperature, or conductance *vs.* temperature (see plot 5), the resulting curves are so steep as to render it impracticable to express the data over an extended temperature range by a single curve. It is found, however, that by plotting the common logarithm of the resistance against temperature, as is done in curve No. III, plot 5, and in plot 6 a convenient line of slight curvature is obtained. It will be seen from this plot that if this curvature is neglected, the results can be represented approximately by the equation

$$\text{Log}_{10} R=a-b\,t \tag{3}$$

This method of expressing the results is very convenient in reducing the data to a basis of resistivity, since combining the relation

$$\rho=K\times R \tag{4}$$

with equation (3) one obtains

$$\text{Log}_{10}\rho=a+\log_{10}K-b\,t=c-b\,t \tag{5}$$

In this equation b and c are constants of the material and are independent of the shape and size of the specimen used. Unfortunately, however, the values obtained for one of these constants depends very markedly upon the other, so that a slight error in one will cause a compensating change in the other. They are, therefore, not well suited for comparing the relative merits of the different materials and for this latter purpose it has been found convenient to compute an "effective temperature" (T_e), which is defined as the temperature at which the

material has the arbitrarily selected resistivity of 1 megohm per centimeter cube, and which may be computed from the equation

$$T_e = \frac{c-6}{b} \tag{6}$$

This value of T_e ranges from 350° in the poorer grades of porcelain up to 800° for fused silica, and is a convenient index of the value of the material as an insulator at high temperatures.

An inspection of these resistance-temperature curves shows a complete absence of any critical temperature at which the material undergoes an abrupt change in its resistance. This shows the error of the commonly accepted idea that porcelain breaks down and becomes conducting at a definite temperature. This belief probably originated from experiments in which the temperature of a porcelain sample was gradually raised while being continuously subjected to an applied voltage. The effect of the current flowing through the sample in such cases would be entirely negligible up to a certain temperature at which the power $\left(\frac{E^2}{R}\right)$ supplied by the measuring current became comparable with the rate at which heat could be dissipated to the surroundings. Owing to the very rapid rate of change of resistance with temperature, a very slight further increase in temperature would materially decrease the resistance and consequently increase the $\left(\frac{E^2}{R}\right)$ loss. Unless the specimen was in a position to give off heat freely to its surroundings the temperature would rise rapidly, causing a further decrease in resistance, thus leading to an unstable state which would rapidly cause the fusion of the material and the passage of an arc. The rapidity of change of resistance with temperature makes this point of instability quite definite, provided all the conditions of the experiment are maintained constant, but this apparent critical temperature will depend very greatly upon the contact between the specimen and the furnace, upon the applied voltage, and the other conditions, so that this is in no sense a specific property of the material.

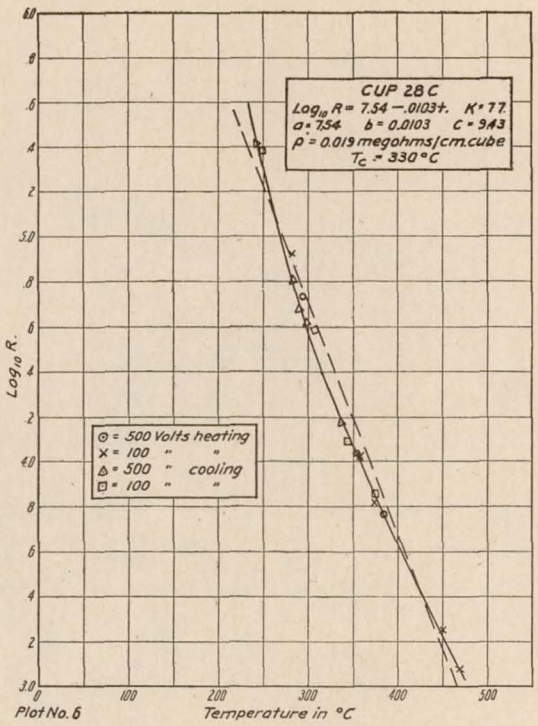
The magnitude of this heating effect is exemplified by the behavior of a porcelain sample tested when hot—for example, at 500° C. At this temperature, the resistance of a centimeter cube of ordinary porcelain is about 100,000 ohms, and if a voltage of only 500 volts per millimeter (i. e., only about one-twentieth of that required to puncture it while cold) be applied, the current flowing will be 50 milliamperes and the power dissipated in the sample will be 250 watts. This will suffice to raise the temperature of the sample at a rate of about 100° C. per second and will cause its rapid destruction.

This heating of the specimen by the measuring current was observed on numerous occasions when making tests at 2,000 and 1,000 volts, and in each case the samples on removal from the furnace were found to contain one or more spots where the porcelain had been fused into a glass by the intense local heating. In the later work at lower voltage this effect was not present, and readings were taken only when the current was substantially constant.

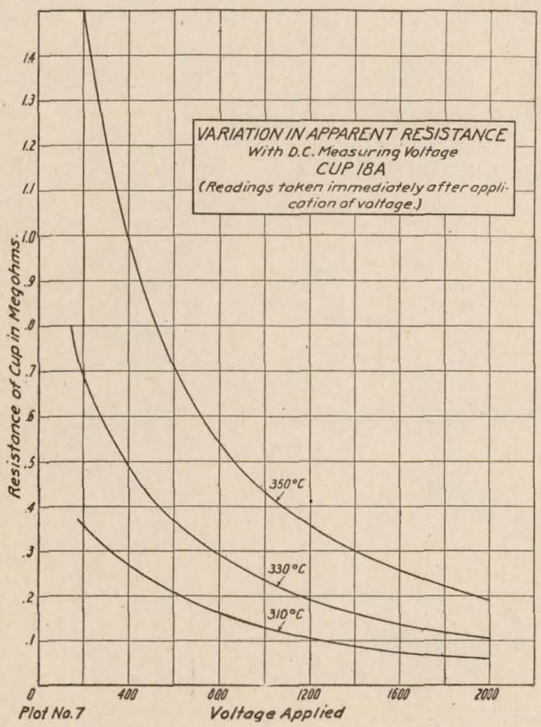
POLARIZATION.

The early measurements with high voltage direct current showed a number of puzzling discrepancies, such as a variation of the apparent resistance with the voltage used in making the measurement and with the time of application of this voltage. Plot 7 shows this variation of resistance with voltage as observed with a porcelain cup specimen. Such discrepancies indicated the presence of an additional phenomenon to be reckoned with, which in the absence of definite knowledge as to its origin was called "polarization," and will be so referred to throughout this report.

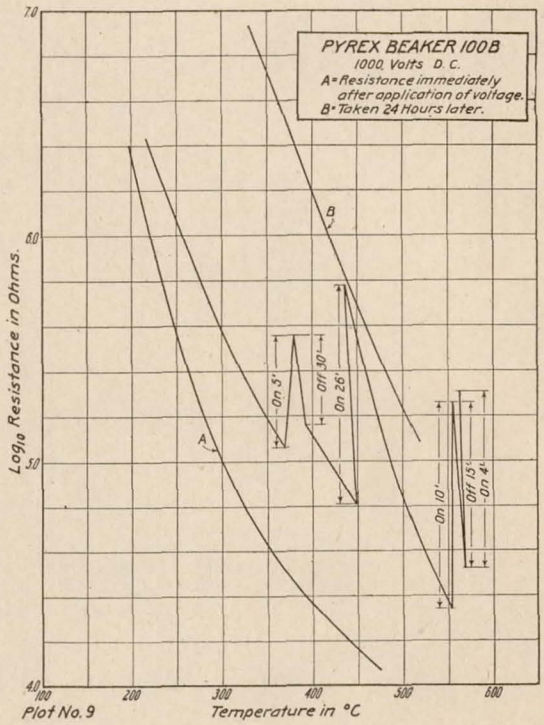
The fundamental manifestation of this so-called polarization is that if a constant direct-current voltage be applied to a specimen, the resulting current will decrease at first rapidly and then more gradually, as is indicated in plot 8. The reduction in current is often equivalent to an increase in resistance by a factor of 10 or 20. If the specimen is allowed to remain at a high temperature but without applied voltage for some time, the effect gradually disappears, but a considerable time is required to accomplish this. The disappearance is more rapid at



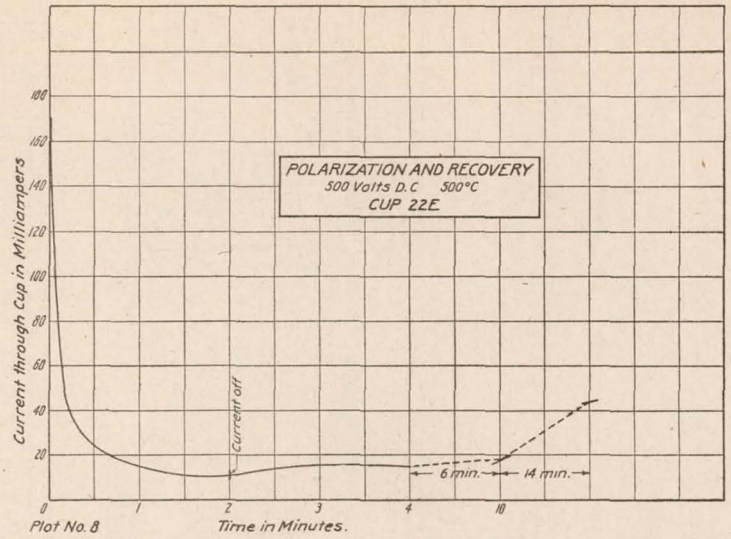
Plot No. 6



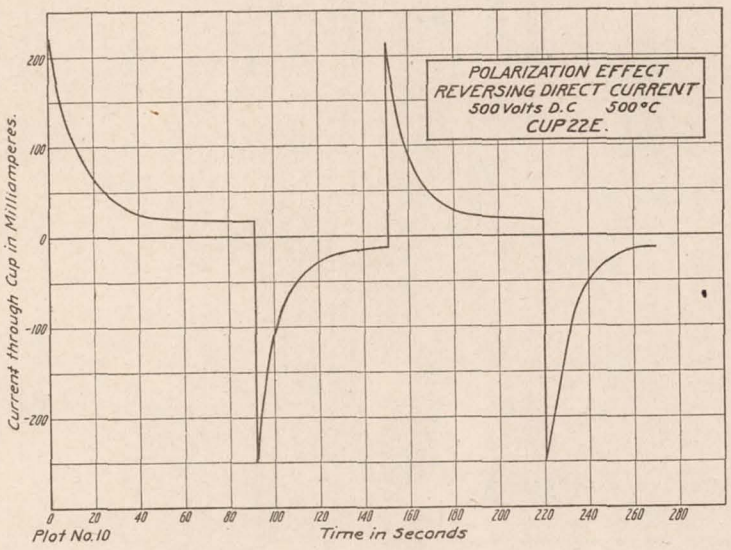
Plot No. 7



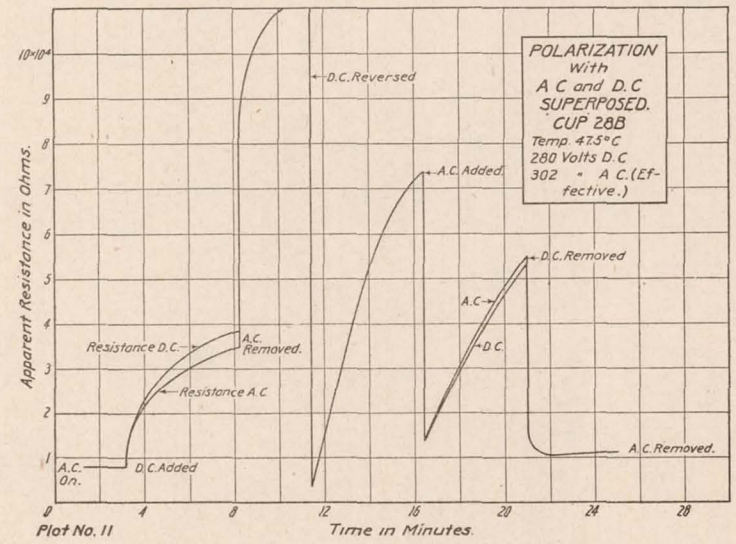
Plot No. 9



Plot No. 8



Plot No. 10



Plot No. 11

high temperatures than at low. Plot 9 gives a record of the variation of the apparent resistance of a glass beaker, as measured with 1,000 volts direct current, after various applications and removals of the measuring potential. The course of the experiment is indicated by the arrows, and the duration of each period of application or of rest is indicated on the curve. The lowest and highest curves give the resistance as observed with very short application of the testing voltage just prior to the polarizing test and on the following day, respectively. The apparent permanent increase of resistance observed with this specimen serves to explain some mysterious results obtained at an earlier date, in which one specimen had shown an increase of resistance to more than twenty times its initial value after several successive tests. The fact that an appreciable time is required to obtain a reading, even with quick acting direct current indicating instruments, and that during this time the specimen is being polarized, is probably a complete explanation of the variation of apparent resistance with applied voltage, shown in plot 7. If the applied direct-current voltage is suddenly reversed after a specimen has become polarized to a considerable extent, the initial current in the new direction is found to be approximately equal in magnitude to the original current and much greater than the value immediately preceding the reversal. (See plot 10.) This implies a counter E. M. F., and an attempt was made to observe such an effect by connecting an electrostatic voltmeter across the specimen. No residual deflection of this meter was observed when the supply current was removed, even after long-continued polarization of the specimen. This result is to some extent in contradiction to facts mentioned by other observers.[2]

A magneto having alternate distributor points of the same polarity connected together was also used as a source of voltage and the polarizing effects found to be in every way similar to those obtained with a steady direct-current source of the same average voltage (150 volts).

When alternating current is applied to a fresh specimen, there is no polarizing effect and the current remains constant indefinitely, except when the current is so large as to produce heating of the specimen. When alternating current is applied to a specimen which has been previously polarized by direct current, the polarization disappears at a more rapid rate than if the alternating current had not been applied.

An attempt to throw light on these complex phenomena was made by applying alternating and direct current simultaneously to a specimen. This was accomplished by connecting a transformer in series with a generator. By opening the primary circuit of the transformer, or the field of the generator, either source of E. M. F. could be eliminated without opening the circuit or interfering with the current flow from the other source. The alternating-current voltage was measured across the transformer terminals with a moving iron voltmeter, and the direct-current voltage by a d'Arsonval type direct-current voltmeter across the generator. The alternating current through the specimen was passed through the moving coil of an electrodynamometer, the fixed coil of which was excited by an alternating current of constant magnitude and in the same phase as the alternating voltage applied to the specimen. The direct current through the specimen was measured by a direct-current milliammeter connected in series with the specimen and the dynamometer. With this arrangement, each pair of instruments measured only its particular component of the resultant current and voltage and was not affected by the presence of the other component. Plot 11 shows the variation with time during the course of the experiments of the resistances as computed from the two components of the current. In this experiment the maximum value of the alternating-current voltage was greater than the direct-current voltage, so that the resultant voltage applied to the specimen reversed in sign during each alternation. Other experiments, in which the maximum alternating voltage was less than the direct-current voltage, and the resultant voltage was consequently unidirectional, showed substantially the same effects.

Throughout the experiments the temperature was held as nearly constant as possible, but a gradual drift of resistance will be noticed which can be accounted for by a slight change of temperature. It appears from these results that the resistance of the specimen is substantially the same for both the alternating and direct current for all states of polarization.

[2] Maxwell, J. C., Electricity and magnetism, § 271, vol. 1, p. 393, 3d ed.

Or, in other words, the polarization produced by the direct current offers resistance to the passage of the alternating current and the depolarization produced by the alternating current reduces the resistance offered to the passage of the direct current.

When alternating current alone was applied to a fresh specimen, the power factor of the circuit was found to be substantially unity. If, however, the specimen had recently been polarized by the application of direct current, the power factor was somewhat reduced; values as low as 0.9 having been observed.

The data described above are quite insufficient for the development of any complete theory of this polarization, but it would appear that the assumption of a counter E. M. F. is ruled out both by the experiments of combined alternating and direct current and by the difficulty of imagining a mechanism capable of producing a counter E. M. F. of the order of several thousand volts, which would be required to produce the observed decrease of current. A possible explanation may be developed on a basis of the migration away from one electrode, of the ions carrying the current, thus leaving a scarcity of carriers for the further passage of current in the original direction, but providing a plentiful supply for currents in the reversed direction. Another suggested explanation is the formation of resisting films which may cover a considerable part of the area of the electrodes but which are readily removed by electrolysis on reversal of the current. Tests made using platinized surfaces as electrodes instead of the melted solder showed no difference of behavior. It may be noticed in this connection that when the samples were removed after cooling, the solidified solder adhered firmly to both surfaces of the cups which had been treated with direct current, but could be very readily peeled off from specimens which had been tested on alternating current.

DISCUSSION OF METHODS FOR MEASURING RESISTANCES.

As a result of the data obtained in the preliminary experiments just described, it was decided to adopt as the most satisfactory method for the rapid comparison of different types of insulating materials the volt-ameter method, using alternating current. Under these conditions the observed resistance is substantially independent of the frequency, voltage, and time of application, and the convenient values of 60 cycles and 500 volts were adopted for the later work. Plot 6 shows typical results obtained by this method and indicates the agreement attainable on successive runs even at different voltages. It should be remembered, however, that the results thus obtained are for the material in the unpolarized state, and, when in actual use in ignition systems, the material may show a much higher resistance to the unidirectional impulse from the magneto.

Of other possible methods for such work, a bridge method using direct current would be objectionable because of the variable amount of polarization which would occur. Attempts were made to use alternating current as a source, but the measurements are complicated by the effect of stray capacities shunting the high resistances which are necessary, and the time required to obtain a balance on the bridge is a serious drawback because of the rapid change in the resistances to be measured with even slight drifts of temperature.

The megger, while extremely rapid and convenient, is open to the disadvantages of polarization and to the fact that the voltage supplied varies very considerably with the resistance of the specimen under test.

The use of a magneto in place of alternating current as a source has the great advantage that it approximately duplicates the conditions of operation in the engine. The magneto, however, is very variable in its ouput, both from instant to instant and as a result of permanent changes in the magnets, contact points, etc. Moreover, there is an abrupt change in the operation of the machine when the resistance of the specimen becomes so low as to cause the spark in the safety gap to cease, and also the total variation of the current delivered with various resistances in the circuit is comparatively slight with this type of machine.

A method involving the measurement of the rate of loss of charge from a condenser connected in parallel with the specimen has been used by Cunningham. This method imitates the conditions of operation much more closely than does the alternating current method, but

not as perfectly as the use of a magneto as a source. The principal objections are the very delicate string electrometer which is required and the necessity of recording the results photographically.

TYPICAL RESULTS AND CONCLUSION.

The following table gives the results obtained by the use of the alternating current method on a number of types of samples, the significance of the various constants being the same as those defined previously.

TABLE 1.

Material.	C	b	T_c	ρ at 500° C.
			°C.	
Fused silica	11.8	0.0065	890	340.10^6
Best porcelain tested	11.2	.0066	790	80
Typical mica plug	12.1	.0085	720	70
Average of three aviation porcelains	11.5	.0085	650	40
Average automobile porcelain	10.2	.0085	490	.80

These figures show a wide variation in the resistance of the different materials but a rather surprising similarity in the constant b, which is a measure of the temperature coefficient of their resistance. It should be mentioned in this connection that while successive measurements with alternating current on a single specimen give results repeating to a few per cent, yet measurements on different specimens of material which are supposed to be identical show wide variations in resistivity, amounting in some cases to a factor of 10. This fact tends to indicate that the conduction is due to a considerable extent to the presence of small amounts of impurities which may vary greatly in amount without appreciably affecting the composition of the material as a whole.

It appears from the above data that the alternating current method developed is very practical and convenient for comparative measurements on samples of this character, but there is a very wide field of investigation concerning the phenomenon of polarization and much interesting work may be done in developing theories as to the precise mechanism by which conduction is carried on in this class of materials.

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REPORT No. 53.

PART II.

ELECTRICAL RESISTANCE OF VARIOUS INSULATING MATERIALS AT HIGH TEMPERATURES.[1]

By R. K. Honeman and E. L. Fonseca.

RÉSUMÉ.

In very hot high-compression engines spark plugs may fail because the core becomes a conductor of electricity. The ignition current then flows through the body of the plug instead of causing a spark at the terminals. The data given in this report show the characteristics of various porcelains and other materials in this respect. These data include values for a large number of plugs now on the market and also various experimental porcelains produced in the laboratory and covering a wide variety of compositions.

To secure definite and repeatable results on this property, it was found necessary to make the measurements with alternating current, using a 500-volt, 60-cycle supply. In this way the disturbing effect of polarization, etc., is avoided. The conductivity of this class of materials increases very rapidly with temperature according to the law of compound interest at a rate of about 2 per cent per degree centigrade.

The most convenient basis of comparison for different materials is the "effective temperature" (T_e) to which they must be heated in order to reduce their resistivity to a definite value. This value is arbitrarily taken as one megohm per cm. cube. A spark plug of normal design with material of this resistivity would have a resistance of about 200,000 ohms. This value is only slightly above the limit at which the usual ignition system can be counted on to fire a plug. The effective temperature thus defined varies from 870° C. in case of fused quartz (the best material tested) down to 280° C. for some kinds of glass. Porcelains have been developed at the Bureau of Standards ceramic laboratory which have an effective temperature as high as 800° C. Certain bodies recently developed for use in aviation engines have temperatures of about 650° C., while the majority of spark-plug porcelains have 500° C. A material having T_e less than 400° C. should be used only when the design of the plug is such that the insulator is extremely well cooled.

INTRODUCTION.

The measurements described below form a part of the investigation of spark plugs undertaken by the Bureau of Standards. A number of cases were reported of spark-plug failures which occurred under conditions suggesting that the insulating material had become conducting at the high temperatures existing in aviation engines, and an extensive study of this phenomenon in various insulating materials was undertaken. Later information combined with data accumulated in the laboratory indicates that this cause of spark-plug failure is not as common as was at first thought, but may occur in very hot engines. The suitability of a material for use in spark plugs should therefore not be judged solely on its insulation resistance while hot.

The ceramic laboratory of the bureau, in connection with this work, undertook to develop an improved type of porcelain which should be more satisfactory for use in spark plugs. As a basis for this a large number of samples of porcelains of various composition were made up so as to obtain data over as wide a field as possible, with the idea of correlating the physical properties of porcelains with their compositions and heat treatment and of obtaining data of value for many lines of work. The ceramic side of this undertaking is described in Part III of this report.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 19.

The early measurements of electrical conductivity, which were made with direct current, showed the existence of very complex phenomena, such as polarization, etc., and it was found necessary to develop an alternating-current method for testing the specimens. The various phenomena observed during the development of this method are discussed in detail in Part I of this report, and in what follows only the method finally adopted and the results obtained by it will be given.

METHOD OF MEASUREMENT.

The specimen of insulating material to be tested is heated in an electric furnace to the desired temperature. Sixty-cycle alternating current at 500 volts is impressed upon the specimen between two suitable electrodes. A voltmeter connected between these electrodes and an ammeter in series with the specimen are read simultaneously and the quotient of effective voltage divided by effective current is taken as the resistance.

Since the current through the specimen is rather small, a very sensitive milliammeter is required and in most of the work it is found most convenient to use for this purpose a dynamometer wattmeter. The fixed coil of this wattmeter is excited by a known current from the same source of supply as the test current through the specimen. The moving coil of the wattmeter is connected in series with the specimen. Such an arrangement provides a higher sensitivity than can be attained with commercial milliammeters, and is also convenient in the great range of currents which can be measured by using various exciting currents. The connections used in this test are shown in figure 1.

Measurements made by this method on the same sample are found to give results agreeing to a few per cent when different voltages, frequencies, and times of application of the measuring current are used. This method has been adopted by the Bureau of Aircraft Production and is recommended in their specification No. 28,017.

Two types of test specimen have been used in this work. For the accurate measurement of the conductivity of the material, a cup specimen, similar to the American Society for Testing Materials, standard test piece No. 1, is very convenient, though it is not essential that the side walls of the cup be tapered. Figure 2 gives a cross section of this type of specimen.

The test cup is filled to a depth of about 2 cm. (0.8 inch) with melted solder, which forms one electrode, and is in turn set in a slightly larger shallow steel cup containing melted solder, which forms the other electrode. This arrangement insures good contact between the electrodes and the porcelain. To avoid cracking the cup it is, of course, necessary to insert the solder in the solid form and melt it by gradually increasing the furnace temperature. Figure 3 shows the arrangement of the cup specimen in the furnace. Two thermocouples protected by porcelain tubes are inserted in the solder in the test specimen and in a hole in the steel cup, respectively. Measurements of resistivity are made only when these two couples indicate substantially the same temperature.

In cases where cup specimens are not available, actual spark plug insulators are tested, using the central electrode as one terminal and the shell of the spark plug as the other. In cases where the insulator is removed from the shell, a band about 2 cm. (0.8 inch) wide at the center of the length of the insulator was coated with platinum by painting it with a solution of platinic chloride ($PtCl_4$) in oil of cloves and then heating the deposit to reduce the chloride to metallic platinum. This platinum belt is used as the outer terminal, and makes good contact with the insulator. The specimen is then inserted, as shown in figure 4, in an electric furnace, in which the temperature is indicated by a thermocouple placed in contact with the shell of the plug.

Measurements obtained on these plug specimens are accurate as indicating the resistance of the specimen, but owing to the irregular shape and the uncertainty as to the area of outer electrode in actual contact with the porcelain they are not suitable for accurately measuring the resistivity of the material. We have, however, computed, from the usual formula [1] for

[1] For concentric cylinders of length L and diameter d_1 and d_2 the factor connecting resistance and resistivity is

$$K=\frac{2\pi L}{\left(\text{Log}_{10}\frac{d_2}{d_1}\right)2.3}$$

For the cup specimens of diameter D and bottom thickness t

$$K=\frac{\pi D^2}{4t}$$

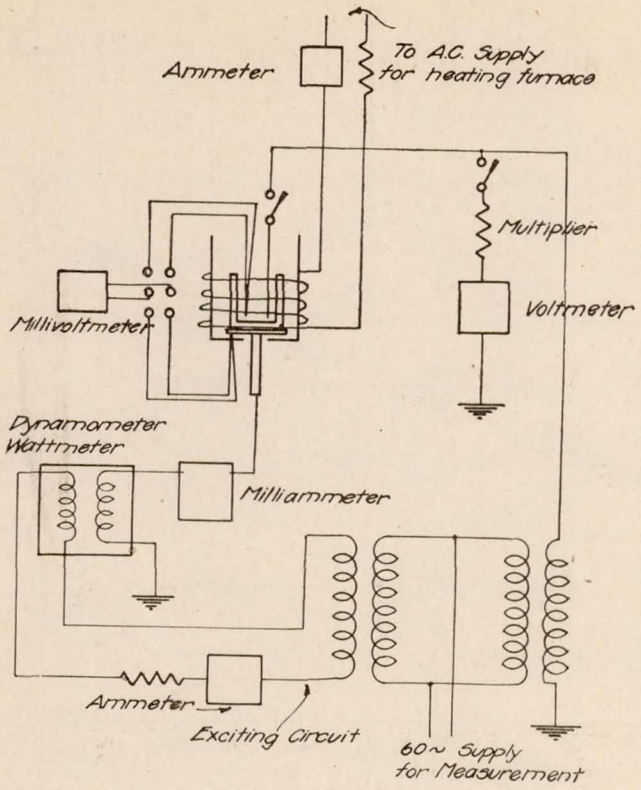


FIGURE 1.

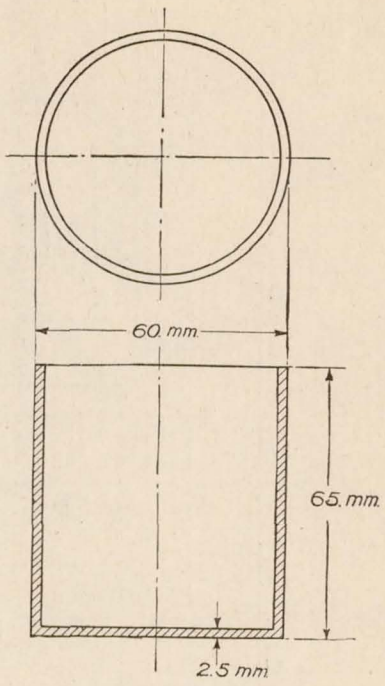


FIGURE 2.
PORCELAIN TEST SPECIMEN.

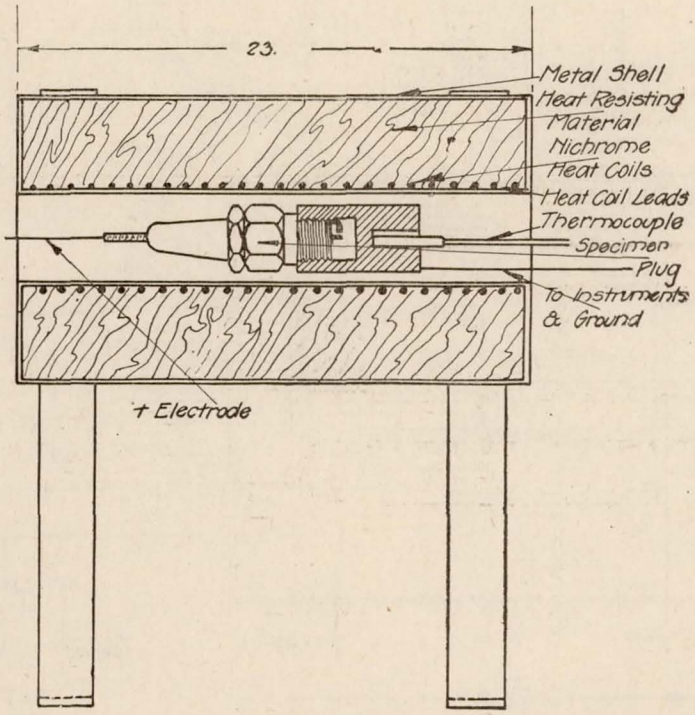


FIGURE 4.

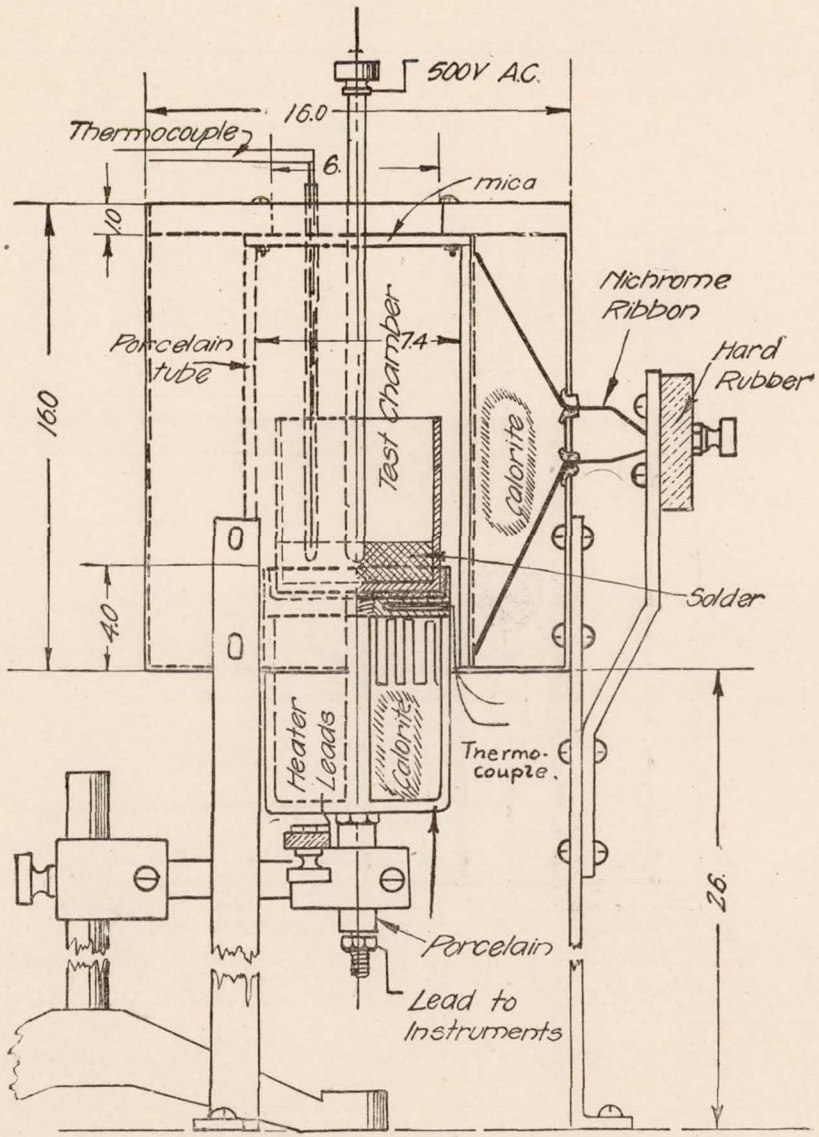
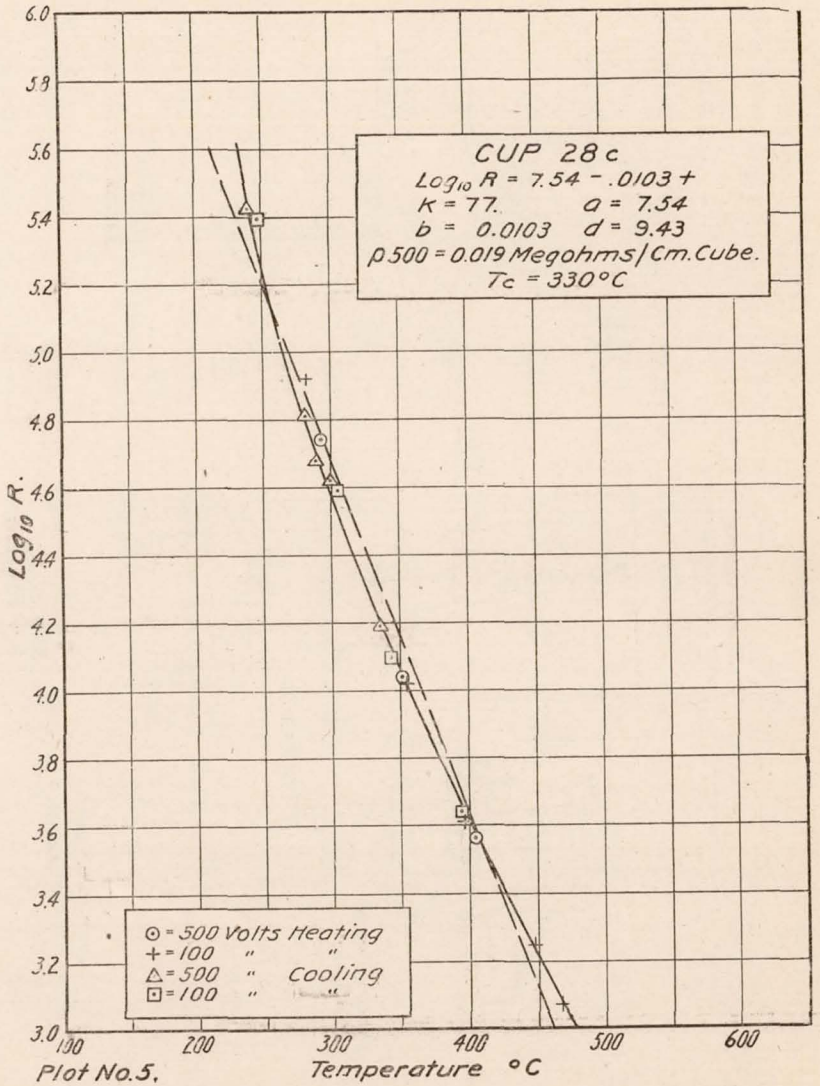

500V A.C.
16.0
Thermocouple
6.
mica
1.0
Nichrome Ribbon
Hard Rubber
Porcelain tube
7.4
Test Chamber
Calorite
16.0
Solder
4.0
Heater Leads
Calorite
Thermo-couple.
26.
Porcelain
Lead to Instruments

FIGURE 3.


CUP 28c
$Log_{10} R = 7.54 - .0103 +$
K = 77. a = 7.54
b = 0.0103 d = 9.43
ρ500 = 0.019 Megohms/Cm. Cube.
Tc = 330°C
⊙ = 500 Volts Heating
+ = 100 " "
△ = 500 " Cooling
⊡ = 100 " "
$Log_{10} R.$
Temperature °C
Plot No. 5.

current flow between concentric cylinders, the factor K, by which the resistance must be multiplied to give the resistivity of the material, and from this factor have computed the resistivities of the plugs, which are given in Tables IV and V. In this computation it has been assumed that contact was made over the entire surface covered by the shell of the plug, and consequently the values of resistivity computed on this basis are too high if this contact be imperfect. It should also be noted that the path for surface leakage is much shorter in the case of the plug specimen, and also that if the glaze is of poorer material than the body conduction through this glaze will reduce the apparent resistivity. In the cup specimen, on the other hand, the area of contact and thickness of the bottom of the cup are definite and easily measured, and any possible leakage path is very long.

COMPUTATION OF RESULTS.

The change of resistivity with temperature for the class of materials tested is so rapid that it is impracticable to plot resistivity vs. temperature directly, as a scale which is suitable at one end of the temperature range becomes extremely crowded at the other. It has been found, however, that by plotting the logarithm of the resistivity against the temperature a smooth curve slightly concave upward is obtained. The curvature of this plot is quite small, and the data can be represented within the range of temperatures used with sufficient accuracy by a straight line [1] which most nearly fits the observed points. Plot 5 shows a typical curve obtained on a cup specimen and also shows the agreement to be expected on repeating the observations on the *same* sample even at different voltages.

The points on the straight line give the relation

$$\text{Log}_{10}R = a - b\,t \tag{1}$$

where R is the resistance of the specimen in ohms and t the temperature in degrees Centigrade, while a and b are constants of the curve. Introducing the factor K mentioned above, we obtain

$$\text{Log}_{10}\rho = a + \log_{10}K - b\,t = c - bt \tag{2}$$

where ρ is the resistivity in ohms per centimeter cube and c a new constant of the material which is obtained from a by the equation

$$c = a + \log_{10}K \tag{3}$$

c and b depend upon the material only and not upon the shape or size of the particular specimen, and from a knowledge of these constants ρ can be computed for any temperature by equation (2). Unfortunately neither c nor b is very convenient as a figure of merit for the material, since a slight error in either will greatly affect the value of the other. We have, therefore, found it advantageous to compute for each material ρ_{500}, which is the resistivity of the material at 500° C. Another still more convenient figure of merit is the temperature at which the material has the definite resistivity of one megohm per centimeter cube.

This can be computed by the equation

$$T_e = \frac{c-6}{b}$$

This value is given in the following tables for each material, and is the most satisfactory criterion of its value as an insulator at high temperatures.

A physical interpretation of the fact that the results when plotted logarithmically give a straight line can be obtained by considering that the conductivity increases with temperature, according to the law of compound interest, at a rate of about 2 per cent (2.3b) per degree Centigrade. The cumulative effect of the compounding is such that an increase in temperature of 100° corresponds in the average material to an increase in the conductivity of 600 per cent.

[1] A slight error is theoretically introduced by this method of representing the results, since the poorer materials are tested at lower temperatures, where the curve is steeper. This is entirely negligible for the purposes for which the results are to be used.

TABLES.

The results of the measurements are given in the tables below. In each table the first column contains a description of the material, the second column gives a number arbitrarily assigned to the specimen for laboratory references, and the remaining columns the value of the constants b, c, T_e, etc., defined in the preceding section.

Table 1 gives the results on the experimental porcelains made up in the ceramic laboratory of the bureau. The composition, heat treatment, etc., corresponding to each of these specimens, is given in Tables 6 and 7.

Table 2 gives similar data on cup specimens which have been submitted by various porcelain manufacturers in connection with their development work.

Table 3 gives results on various other materials which were obtained in the form of crucibles, tubing, etc., by the laboratory.

Tables 4 and 5 contain the results on American and foreign spark plugs, respectively.

Table 6 gives the compositions and firing temperatures (in terms of Orton's pyrometric cones) of the various materials listed in Table 1. The various calcines mentioned in this table are described in Table 7.

The numerical values in the tables are in each case the average of the results of all the samples tested of the same material, but in many cases only one sample was tested. Unfortunately, the variation in T_e observed in different specimens of what was supposed to be the same material sometimes amounts to as much as 50° C, and this variation should be borne in mind in comparing the results on different materials.

It should also be noted that where both cup and plug samples of nominally the same material were tested the latter usually showed decidedly lower resistance. Three explanations for this may be suggested:

First. The material is made up by a somewhat different process, the cup specimens being molded under slight pressure while the plugs are extruded through a die.

Second. Surface leakage and conduction through the glaze may have been present in the plug specimens and not in the cups.

Third. The cup specimens being especially prepared for test, may have been made up with greater care than the plugs.

CONCLUSIONS.

The following conclusions seem evident from the data given in the tables.

Quartz is by far the best of the materials tested as far as resistance at high temperature is concerned, although several of the laboratory porcelain bodies, such as 77 and 78, approach this fairly closely. The mica plugs show fairly high resistivity, but it should be noted also that this material loses its water of crystallization at temperatures approaching 1,000° C. and becomes very soft and friable.

Several of the porcelains recently developed in this country for aviation work are very notably superior to the majority of the porcelains tested.

The steatite and Rajah porcelains from Germany are not notably high in resistivity, and therefore the very high reputation as spark plug insulators which these materials had before the war was apparently not due to their resistivity. The French porcelains are on the whole not as good as the more recent American bodies. This may account for the preference for mica plugs shown in the former country.

TABLE 1.—*Bureau of Standards cups.*

Cup No.—	*b.*	*c.*	Resistivity at 500° C. ρ_{500} megohms.	Effective temp. °C. T_e.
16	0.0135	13.58	6.8	560
17	.0089	9.50	.11	390
18	.0070	9.09	.39	440
22	.0089	9.33	.08	370
23	.0096	10.30	.32	450
24	.0085	9.27	.10	380
28	.0085	9.04	.062	358
32[1]	.0084	9.34	.14	400
35	.0108	11.02	.42	460
36	.0109	10.34	.078	400
39	.0125	10.84	.039	390
40	.0080	9.28	.19	410
47[1]	.0091	9.62	.12	400
48	.0105	10.26	.10	410
49	.0076	9.07	.19	400
50	.0113	10.43	.060	390
55	.0119	10.77	.066	400
63	.0090	10.85	2.2	540
70	.0097	10.46	.41	460
72[1]	.0098	10.89	.40	500
73	.0081	9.64	.39	450
74[1]	.0099	12.37	26	640
77	.0065	11.17	83	800
78	.0066	11.21	81	790
79	.0080	11.11	13	640
88	.0092	11.38	6	590
94[1]	.0119	13.32	23	620
95[2]	.0089	11.58	13	630
107	.0083	9.96	.65	480
109	.0069	10.18	5.4	610
116	.0071	11.18	43	730
119	.0075	11.51	58	730
152[3]	.0073	11.03	24	690
180	.0074	10.77	12	640

[1] Average two determinations. [2] Average five determinations. [3] Average three determinations.

TABLE 2.—*Cups from manufacturers.*

Maker.	No.	*b.*	*c.*	Resistivity at 500° C. ρ_{500} megohms.	Effective temp. °C. T_e.
Jeffery Dewitt	2	0.0071	9.82	1.9	540
Jeffery Dewitt	3	.0088	10.83	2.7	550
Jeffery Dewitt	5	.0091	11.98	27	660
Champion Ignition Co	11	.0083	11.11	9.1	620
Champion Ignition Co	17	.0075	10.57	6.6	610
Herold	451A	.0092	9.65	.11	400
Frenchtown	577	.0076	10.24	2.8	560
Frenchtown	315	.0114	10.12	.026	360
Frenchtown	280	.0107	9.74	.025	350
Frenchtown	775	.0080	11.10	12	640
Frenchtown	775X	.0080	11.14	14	640
Frenchtown	775BG	.0084	10.76	3.6	570
Frenchtown	28BG	.0087	10.10	.56	470
Frenchtown	783	.0090	10.20	.50	470
Frenchtown	741	.0077	10.70	7.1	610
Frenchtown	56	.0064	9.80	4.0	590
Brunt	150	.0069	9.78	2.1	550
Brunt	154	.0097	11.81	9.1	600

Jeffery Dewitt (supply Champion Toledo plugs). Frenchtown (supply Bethlehem and other plugs). Champion Ignition Co. (supply A. C. Titan plugs).

TABLE 3.—*Miscellaneous specimens.*

Material.	*b.*	*c.*	Resistivity at 500° C. ρ_{500} megohms.	Effective temp. °C. T_e.
Fire clay	0.0081	10.43	2.4	550
Pyrex crucible	.0094	9.56	.072	380
Pyrex glass tube	.0092	9.14	.035	340
Soda glass	.0214	13.5	.00063	350
Quartz	.0065	11.7	282.0	880
Large quartz tube	.0049	10.28	68	870
Small quartz tube	.0034	8.35	4.5	690

TABLE 4.—*American plugs.*

Plug.	No.	b	a	c	$\text{Log}_{10} K$.	Resistivity at 500° C. ρ_{500} megohms.	Resistance at 500° C. R 500 megohms.	Effective Temp. °C. T_e.
PORCELAIN.								
Bethlehem	611	0.0070	8.97	9.69	0.72	1.55	0.36	530
Bethlehem Aviation	1668	.0061	7.82	8.40	.58	.22	.059	390
Berkshire	128	.0095	9.05	9.47	.42	.052	.020	360
(3141) Champion [1]	231–041	.0078	9.32	9.77	.45	.74	.26	480
Champion (old)		.0082	9.63	10.00	.37	.79	.34	490
Champion (Toledo)	1812	.0088	10.74	10.99	.25	3.99	2.19	570
Champion, Toledo (3450)	1823	.0061	8.56	8.81	.25	.58	.32	460
B. S. Champion, Toledo	3496	.0053	8.77	8.92	.15	1.9	1.32	550
Do	3518	.0032	7.16	7.31	.15	.51	.36	410
Harding's insul		.0042	7.56	7.92	.36	.66	.29	460
Do	Red.	.0124	11.54	12.05	.51	.71	.22	490
Do	Gray.	.0102	10.47	11.25	.78	1.4	.23	510
Do	Hercules.	.0077	10.15	10.81	.66	9.1	1.99	620
Coors, Herold		.0065	8.10	8.37	.27	.13	.07	360
Do	C-4	.0086	9.29	9.56	.27	.18	.098	410
Do [2]	C-5	.0070	8.87	9.14	.27	.44	.23	450
Duffy [2]		.0069	9.18	9.62	.44	1.5	.54	520
Frenchtown	Beth. Avia.	.0093	10.67	10.74	.064	1.23	1.05	510
Do	56	.0088	11.23	11.48	.25	12.0	6.8	620
Do	884	.0066	8.50	9.07	.57	.59	.16	470
Hercules	1818	.0057	8.69	9.35	.66	3.36	.69	590
Mosler [2]	793–022	.0084	9.51	10.16	.66	.91	.20	500
Mohawk		.0087	9.52	10.01	.49	.46	.15	460
Randall	45	.0075	9.22	9.79	.57	1.0	.29	500
Rajah (German) [2]		.0078	8.61	8.68	.07	.060	.05	340
Rajah (Empire) [2]	45	.0071	8.30	8.47	.171	.083	.056	350
Rajah (Coors)		.0080	8.86	8.93	.07	.085	.072	370
Red Head	.056	.0076	7.08	7.74	.66	.008	.0019	230
Titan A. C [2]	15.458	.0079	8.57	9.21	.63	.18	.04	410
Cico A. C		.0052	7.01	7.63	.61	.117	.026	310
Valve plug	.028	.0056	8.50	8.61	.11	.65	.50	470
Walden-Worcester	*X* 7	.0069	8.30	8.75	.45	.20	.07	400
MICA.								
Splitdorf	873	.0078	9.08	10.28	1.20	2.4	.15	550
Splitdorf, G. J	1819	.0078	9.59	10.79	1.20	7.8	.15	614
Bethlehem	397	.0143	13.73	15.00	1.25	71.0	3.80	630
Berkshire	110	.0053	9.25	9.93	.68	19.0	3.98	700
GLASS.								
Anderson	294	.0100	8.88	9.35	.47	.022	.008	335
Do [4]	653	.0158	10.87	12.18	1.31	.92	.001	390
Do	655	.0128	9.70	11.01	1.31	.04	.002	390
LAVA.								
Duffy		.0064	8.51	9.20	.69	1.00	.20	500
G. E	*X* 16	.0058	9.25	10.17	.92	18.0	.240	720
STEATITE.								
Herz Bougie	332	.0098	9.63	10.16	.53	.18	.054	420
Do	1827	.0098	11.83	12.37	.54	29.0	8.5	655

[1] Average of eight determinations.
[2] Average of two determinations.
[3] Average of four determinations.
[4] Pyrex and glass.

TABLE 5.—*Foreign plugs.*

Plug.	B. S. No.	Material.	b	a	c	$\text{Log}_{10} K$.	Resistivity at 500° ρ_{500} megohms.	Resistance at 500° C. R. 500 megohms.	Effective temp. °C. T_e.
Re 'V	456	Porcelain	0.0096	9.51	10.53	1.02	0.54	0.051	470
Oleo	439	.....do	.0086	9.10	10.07	.97	.61	.063	470
Joly [1]	421	.....do	.0085	9.39	10.26	.86	1.0	.14	500
Pognon		Composition	.0066	8.46	9.19	.76	.78	.14	480
Fert		Porcelain	.0078	8.57	9.15	.58	.18	.047	400

[1] Average three determinations.

TABLE 6.—*Spark plug compositions.*

B. S. body No.	Georgia kaolin.	Florida kaolin.	North Carolina kaolin.	Delaware kaolin.	Maine feldspar.	Flint.	Whiting.	Tennessee ball clay No. 5.	Kentucky ball clay No. 4.	Calcined Florida kaolin.	Calcine-kaoline, equal parts of four.	Calcine No. 3.	Calcine No. 19.	Calcine No. 20.	Calcine No. 13.	Calcine No. 14.	$Zr O_2$.	Maturing temperature in standard cones.
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	
16	11.25	11.25	11 25	11.25	16.00	39.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	16 down.
17	11.25	11.25	11.25	11.25	18.00	37.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	15 down.
18	11 25	11.25	11.25	11.25	20.00	35 00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	14 down.
22	11.25	11 25	11.25	11.25	28.00	27.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	14 half over.
23	11.25	11.25	11.25	11.25	30.00	25.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	13 half over.
24	12.50	12.50	12.50	12.50	16.00	34.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	15 down.
28	12.50	12.50	12.50	12.50	24.00	26.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	14 half over.
32	13.75	13.75	13.75	13.75	14.50	29.00	1.50	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Do.
35	13.75	13.75	13.75	13.75	20.50	23.00	1.50	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	12 down.
36	13.75	13.75	13.75	13.75	22.50	21.00	1.50	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Do.
39	13.75	13.75	13.75	13.75	28.50	15.00	1.50	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Do.
40	15.00	15.00	15.00	15.00	16.00	24.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	13 down.
47	15.00	15.00	15.00	15.00	30.00	10.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	10 down.
48	12.50	12.50	12.50	12.50	24.00	5.00	1.00	.....	.....	20.00	.....	.....	.....	.....	.....	.....	.....	14 down.
49	12.50	12.50	12.50	12.50	22.00	12.00	1.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	Do.
50	12.75	12.75	12.75	12.75	25.00	.....	1.50	.....	.....	.....	.....	.....	22.50	.....	.....	.....	.....	Do.
55	12.50	12.50	12.50	12.50	28.50	.....	1.50	.....	.....	.....	20.00	.....	.....	.....	.....	.....	.....	14 half over.
63	12.50	12.50	12.50	12.50	13.50	.....	1.50	.....	.....	.....	35.00	.....	.....	.....	.....	.....	.....	16 down.
70	12.50	12.50	12 50	12.50	16.40	.....	1.00	.....	.....	.....	.....	4.10	28.50	.....	.....	.....	.....	14 down.
72	10.00	9.00	9.00	9.00	22.00	.....	.....	5.00	.....	.....	.....	.....	.....	.....	.....	.....	36.00	13 down.
73	10.00	9.00	9.00	9.00	17.60	.....	.....	5.00	.....	.....	.....	4.40	.....	.....	.....	.....	36.00	Do.
74	.....	.....	.....	.....	.....	.....	.....	7.50	7.50	.....	.....	.....	.....	85.00	.....	.....	.....	Do.
77	1.25	1.25	1.25	1.25	.....	.....	.....	5.00	5.00	.....	.....	.....	.....	85.00	.....	.....	.....	Do.
78	2.50	2.50	2.50	2.50	.....	.....	.....	5.00	5.00	.....	.....	.....	.....	80.00	.....	.....	.....	Do.
79	2.50	2.50	2.50	2.50	.....	.....	.....	7.50	7.50	.....	.....	.....	.....	75.00	.....	.....	.....	Do.
88	12.50	12.50	12.50	12.50	8.00	30.00	.....	.....	.....	.....	.....	.....	.....	.....	12.00	.....	Al_2O_3	15 half over
94	11.25	11.25	11.25	11.25	17.60	.....	.....	.....	.....	.....	.....	.....	.....	.....	4.40	.....	33.00	16 down.
95	10.00	10.00	10.00	10.00	.....	42.00	$MgCO_3$	.....	.....	.....	.....	.....	.....	.....	.....	18.00	.....	20 down.
107	10.00	10.00	13.50	13.50	14.00	21.00	10.00	4.00	4.00	Calc.8A	.....	.....	.....	.....	.....	.....	.....	12 down.
109	8.00	8.00	.....	9.00	.....	.....	.....	10.00	10.00	20.00	35.00	.....	.....	.....	.....	.....	.....	16 down.
116	12.50	12.50	12.50	12.50	.....	30.00	.....	.....	.....	.....	.....	.....	.....	.....	20.00	.....	.....	18 down.
119	12.50	12.50	12.50	12.50	.....	30.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	20.00	.....	Do.
152	7.50	7.50	7.50	7.50	.....	.....	$MgCO_3$	5.00	5.00	.....	.....	.....	40.00	.....	.....	20.00	Al_2O_3	16 down.
180	6.87	6.87	27.75	27.50	.....	5.75	4.58	4.58	4.58	.....	.....	.....	.....	.....	.....	.....	11.52	20 down.

TABLE 7.—*Spark plug calcines.*

B. of S. calcine, No.	$MgCO_3$.	Kaolin.	Flint.	Calcines, Al_2O_3.	Boric acid.	Calcining temperature.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Cone.*
3	39.50	60.50	.....	.....	.....	10
8 A	14.40	44.30	41.30	.....	.....	12
13	23.85	76.15	.....	.....	.....	12
14	18.20	56.00	25.80	.....	.....	13
19	.....	70.20	.....	27.80	2.00	20
20	34.30	.....	65.70	.....	.....	16

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REPORT No. 53.

PART III.

PREPARATION AND COMPOSITION OF CERAMIC BODIES FOR SPARK PLUG INSULATORS.[1]

By A. V. Bleininger.

RÉSUMÉ.

In airplane engines the porcelain of the spark plugs is subjected to severe conditions, involving high temperatures, sudden heating and cooling effects, and mechanical stresses. To be perfectly suited for the purpose, the material must remain a good electrical insulator at the maximum temperature reached, should not be subject to permanent volume changes, should possess constant thermal expansion, and must be strong and tough.

Porcelains possessing such qualities have been developed in the Pittsburgh laboratory of the Bureau of Standards. The compositions of the best types are as follows:

Porcelain No. 152.

	Per cent.
Georgia kaolin	10
Florida kaolin	10
North Carolina kaolin	10
Delaware kaolin	10
Calcine No. 19	40
Calcine No. 14	20

The compositions of the calcines are:

	Calcine No. 19.	Calcine No. 14.
Kaolin	70.20	56.00
Alumina	27.80	.....
Magnesium carbonate (precipitated)	.....	18.20
Potters flint	.....	25.80
Boric acid	2.00	.....

Porcelain No. 194.

	Per cent.
Beryl	35.0
Georgia kaolin	12.5
Florida kaolin	12.5
North Carolina kaolin	12.5
Delaware kaolin	12.5
Potters flint	15.0

PORCELAINS FOR SPARK PLUGS.

The average commercial porcelain does not fulfill the conditions required for spark-plug service, nor for any other conditions where high-tension currents are employed, and the temperature is considerably above atmospheric conditions. From the standpoint of the electrical resistance at the temperatures reached in airplane engines, the feldspathic porcelains begin to break down at a rate rapidly increasing with temperature, due to electrolytic effects. This is indicated also by the polarization which is observed in using direct current. The leakage thus taking place may become a serious factor.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 23.

This average porcelain is likewise not constant in volume; and these volumetric changes are greater than can be explained solely by thermal expansion. Aside from the thermal expansion, the quartz content of porcelain, when heated or cooled, is subject to certain modifications in crystalline structure, accompanied by definite volume changes. Thus, the form of quartz permanent at atmospheric temperature is alpha quartz, which inverts to beta quartz at 570° C, a transformation which is reversed by cooling. On the other hand if, in the firing of porcelain, the quartz is inverted to its high temperature form, cristobalite, there is again the transformation of the alpha to the beta modification to be considered, which takes place at 230° C. In either case, volume changes are unavoidable in all porcelains containing free quartz in large amounts, due to the inversion noted. In a good spark-plug porcelain, the quartz should be eliminated from the compound and replaced by a substance not subject to these inversions.

Another defect of the ordinary porcelain is that the coefficient of thermal expansion is by no means constant at different temperatures. It may be 19×10^{-6} between 30—200° C and 5×10^{-6} between 400—500° C.

With respect to mechanical strength, also, great variations are possible. A series of tests of commercial electrical porcelains, conducted at the Pittsburgh laboratory of the Bureau of Standards, showed differences in the modulus of elasticity varying from 1,600,000 to 6,000,000.

For the purpose of studying porcelains from the standpoint of their electrical conductivity at the high temperatures obtaining in airplane ignition systems, a large number of typical compositions were made up in the form of the test cups illustrated in figure 2 of Part II of this report. These mixtures were usually prepared in 10-kilogram batches, carefully weighed out and ground wet, in porcelain-lined ball mills for three hours. The suspension of clay was pumped into a filter press to remove the water, and then kneaded in a mixing machine to the consistency required for shaping the mass on the potters wheel. This was done by the use of plaster molds in which the cups were "jiggered" in the usual manner in which pottery is made. The specimens were then dried, placed in fire-clay containers (saggers) and burned in a down-draft kiln fired with natural gas to the finishing temperature. The latter was controlled both by means of thermocouples with the necessary galvanometers, and pyrometric cones, made by Edward Orton, Columbus, Ohio. Each cup was examined for nonabsorption by the application of ink. The testing of the specimens was done at the Washington laboratory as described in Part II of this report. The characteristic expression for the resistivity of the porcelains is the T_e value which represents the temperature in °C. at which a cubic centimeter of the material still shows a resistance of one megohm.

REPLACEMENT OF FELDSPAR.

Upon comparing the T_e values of the different porcelains it was noted that there exists no definite relation between the composition and the electrical conductivity. On the other hand, the higher the maturing temperatures of the porcelains, the higher was the T_e value. This is practically equivalent to saying that, roughly speaking, the electrical resistance at higher temperatures is the greater the lower the feldspar content, since small amounts of this flux make it necessary to carry the porcelain to a higher burning temperature. The relation, however, is not well defined, as may be observed from the results compiled in the following table:

TABLE I.

No. of body.	Feldspar.	Maturing temperature in cones.	T_e value.
	Per cent.		
16	16	16	560
17	18	15	390
18	20	14	440
22	28	[1] 14	370
23	30	13	450

[1] Half over.

It is quite evident that the micro-structure of the porcelains is an important factor in this connection, since it can not be immaterial how much kaolin or quartz has been dissolved by the fused feldspar and how much sillimanite has been formed. The evidence, however, was considered sufficient to warrant the replacement of the feldspars by other fluxes, the oxides of magnesium and beryllium being used for this purpose.

Owing to the evolution of carbon dioxide during the firing process from magnesite, and the artificially prepared basic magnesium carbonate, and the very large shrinkage accompanying their use as a flux, it was decided to introduce the magnesia in the form of a calcine; that is, a silicate mixture previously fired to a point close to vitrification. The mixtures employed for this purpose correspond to the formula: $MgO\ Al_2O_3\ 2SiO_2$; $MgO\ Al_2O_3\ 4SiO_2$, and $MgO\ Al_2O_3\ 6SiO_2$. Of these, the first and the second were most used in this work. The preparation of the calcines consisted in dry ball mill grinding and firing the mixture made up into balls with just sufficient water. After calcination, the material was crushed and ground and introduced into the bodies in this form. The beryllium oxide was brought in through the use of the mineral beryl (which has the general composition $3BeO\ Al_2O_3\ 6SiO_2$) without any previous treatment.

With the use of magnesia as the principal flux, the electrical resistance and hence the value T_e, was found to increase quite decidedly, though with no well-defined regularity as referred to percentage content of magnesia. It was seen again in this connection, that the structure of the porcelain plays an important part especially as it is known that MgO accelerates the crystallization of sillimanite most vigorously. Not only the number but also the size of the sillimanite crystals is of significance in determining the texture of the body, whether it is to be fine grained, glassy, or coarsely crystalline. The rate of cooling the porcelain is likewise of importance, since a rapid drop in temperature invariably causes the structure to be closer and of more vitreous character than when a longer time is taken in cooling down the kiln. For this reason smaller kilns are to be preferred to larger ones, since they require less time in cooling at a given rate. The effect of magnesia added in the form of synthetic silicate, is strikingly shown by the high T_e values of bodies Nos. 77 and 78. See Table IV.

It is a fact that the magnesium silicates show electrolytic effects which are much less prominent than when feldspar, an alkali-aluminum silicate ($K_2O\ Al_2O_3\ 6SiO_2$) is used as a flux. It likewise appears that the higher the firing temperature of the porcelain the greater its electrical resistance, at temperatures up to 700° C., or somewhat above this point.

With reference to the use of beryllium oxide it was found that this flux behaves similarly to the magnesia in showing high electrical resistance and T_e values. This is indicated by the following table:

TABLE II.

No.	Beryl.	Kaolin.	Flint	Maturing temperature of porcelain in cones.	T_e
	Per cent.	*Per cent.*	*Per cent.*		
193	25	50	25	12	624
194	35	50	15	11	784
195	45	50	5	11	798

It is evident from these results that beryllium oxide, used in the form of the mineral beryl, is a valuable flux from the standpoint here under consideration. It requires, however, careful temperature control in firing, since the beryllium porcelain is subject to sudden deformation as the vitrification temperature is exceeded. The experiments have proven that beryllium oxide is worthy of consideration for the production of such porcelain, and the high T_e value obtained, 798, is exceedingly promising. The firing temperature of these bodies is quite low, from cones 11–12.

Another interesting fact developed with reference to the thermal expansion of the beryllium porcelain, which was found to be lower than that of the feldspathic bodies commonly employed. The average coefficient was found to be 1.63×10^{-6} for the temperature interval 26—200° C.; 2.95×10^{-6} for 200—400°; 3.60×10^{-6} for 400—570°; and 2.33×10^{-6} for 26—400°.

REPLACEMENT OF QUARTZ.

From a general study of porcelains, it appears desirable to eliminate the quartz, as has been pointed out in a previous paragraph. Some of the materials available for this purpose are calcined kaolin, synthetically prepared sillimanite (Al_2O_3 SiO_2), and sintered or fused alumina and zirconium oxide. These substances have been introduced in a number of compositions. The effect of adding calcined kaolin in general was beneficial; and even with a feldspar content of 13.5 per cent (body No. 63), a fair T_e value, 540, was obtained. This particular composition contained 50 per cent raw kaolin, 13.5 per cent feldspar, 1.5 per cent calcium carbonate, and 35 per cent calcined kaolin. The maturing temperature of this porcelain was that corresponding to cone No. 16. It is evident that by raising the content of calcined kaolin still more at the expense of the feldspar a higher T_e value would be obtained. The introduction of plastic ball clay to replace kaolin, invariably and in all types of bodies, reduces the electrical resistance within the temperature range here under consideration.

The use of fused alumina in any extensive work was prohibited by the lack of material low in iron content. The commercial substance (alundum) is unsuited for this purpose. The total amount of white fused alumina available was not more than 2 pounds. To bring about the necessary impervious and dense structure the use of 17.6 per cent of feldspar was required. A mixture consisting of 45 per cent kaolin, 17.6 per cent feldspar, 4.4 per cent calcine No. 13, and 33 per cent of alundum, resulted in a very tough porcelain which showed a T_e value of 620. Calcine No. 13 was compounded according to the formula MgO Al_2O_3 $2SiO_2$ from 84 parts, by weight, of magnesium carbonate and 258 of plastic kaolin from Florida and Georgia. Here again the reduction of the feldspar content and its replacement by calcine No. 13, or beryl, or a combination of these two would be certain to raise the T_e value considerably and at the same time would result in a porcelain of excellent mechanical properties. The cost of the fused white alumina would be quite high, but would be justified under the circumstances. Furthermore, a single calcine could be readily produced by combining the raw materials of calcine No. 13, the kaolin and magnesite, with uncalcined alumina from any convenient source, and firing the mixture to a point of constant volume, which could be accomplished at temperatures not exceeding cone No. 18. At the same time this procedure would simplify the process of preparation very considerably.

Sillimanite ($Al_2O_3SiO_2$) is a normal component of all hard fired porcelain; and this constituent, if not present in the form of large crystals, imparts to the material constancy in volume upon heating, lowers the thermal expansion, increases the refractoriness, and the resistance to sudden heating and cooling. For this reason it was thought desirable to produce the mineral synthetically and to introduce it in the porcelain composition in place of the quartz. This was done by combining 70.20 per cent of plastic kaolin, 27.80 of anhydrous alumina, and 2 per cent of boric acid. After grinding this mixture in the dry state in a ball mill, it was made up with water to form a plastic mass which was molded into balls calcined to a temperature corresponding to that of cone No. 20, or approximately 1,530° C. At this temperature the mass sintered to a dense structure, subject to but little additional shrinkage and containing only a small amount of uncombined alumina. The boric acid was added to assist in bringing about the necessary shrinkage and closing up of the pores, and it is quite probable that most of this constituent is volatilized at the final temperature of the calcination. This calcine (No. 19) was then crushed separately, passed over a magnetic separator, and then ground, together with the other materials of the body with the addition of water, in the ball mill. In preparing this type of body the feldspar was eliminated on the basis of the results discussed above, and replaced by a calcine corresponding to the formula MgO Al_2O_3 $4SiO_2$ (No. 14). This porcelain (No. 152) was composed of 30 per cent of kaolin, 10 per cent of ball clay, 40 per cent of sillimanite calcine, and 20 per cent of fluxing calcine No. 14, and fired to a temperature of cone No. 16 or higher. The resultant material had excellent mechanical qualities and an average T_e value of 690. The structure of this body should be fine and dense, a condition which requires quite rapid cooling of the kiln. Slower cooling results in the formation of coarser sillimanite crystals which cause a structure much less resistant to sudden heating and cooling.

The preparation of this body may be simplified by the combination of the two calcines into one, thus, by employing the composition of the flux No. 13 ($MgO\ Al_2O_3\ 2SiO_2$) the combined calcine would be composed of 75.10 per cent plastic kaolin, 8.77 per cent magnesite, and 16.13 per cent anhydrous alumina. The boric acid content has been eliminated. Body No. 152 would then consist of 30 per cent of kaolin, 10 per cent of ball clay, and 60 per cent of the combined calcine. Wherever the working conditions permit the ball clay should be eliminated, and an effort made to employ the body containing 40 per cent of plastic kaolin, which can usually be done by allowing the mixture to age before molding it.

The tendency of the body to crystallize may be diminished also by replacing the fluxing calcine in part by beryl, so that these two components are present in the ratio of 1:1. If, then, the combined fluxing and sillimanite calcine is employed, the resultant composition would be kaolin, 60.94 per cent; anhydrous alumina, 18.39 per cent; boric acid, 1.32 per cent; magnesite, 4.58 per cent; beryl, 14.78 per cent. The body, as before, would consist of 60 per cent of this calcine and 40 per cent of kaolin. The fusion point of this mixture is so low that it would be quite possible to eliminate the boric acid entirely. At the same time the vitrification point of the body is lower and closer to the normal kiln temperatures.

Attention might be called to the fact that the use of a siliceous porcelain is not objectionable from the electrical standpoint but only from consideration of the mechanical strength, resistance to sudden temperature changes, etc. This is shown by the results upon high silica porcelains, bodies Nos. 116 and 119, which show a very high T_e value, namely 730. This type of porcelain contains 50 per cent of clay, 30 per cent of free quartz (flint), and 20 per cent of magnesia calcine. In No. 116, the calcine corresponds to the formula $MgO\ Al_2O_3\ 2SiO_2$, and in No. 119 to $MgO\ Al_2O_3\ 4SiO_2$. It is fair to state those porcelains would give excellent results, considered from the dielectric standpoint, when used under conditions not so extreme with reference to temperature and shock as is the case with spark plugs used in airplane engines.

Zirconium oxide was used only in two porcelains, due to the comparatively limited supply available. The material at hand was zircon which contained 52.74 per cent of ZrO_2 and 43.46 per cent of silica. As received, the mineral was high in iron, which, however, was eliminated by treatment with chlorine at a temperature of 800° C. In this manner all but a trace of the iron was removed. Owing to the fact that these zircon porcelains were produced comparatively early in the work, feldspar was employed as the flux. The result was that the electrical resistance, and hence the T_e value, was low, being 500 and 450, respectively. With the use of the magnesia or beryllium fluxes much better products could undoubtedly be produced. The mechanical strength of these porcelains was excellent in every respect. The composition of these bodies, Nos. 72 and 73, is given in Table IV.

The effect of the quartz in porcelain upon the thermal expansion of the body is shown by the results compiled in Table III.

TABLE III.

No.	Clay.	Quartz (flint).	MgO calcine.	Formula of MgO calcine.	Sillimanite calcine.	Coefficient of thermal expansion $\times 10^6$.			
						30–200 °C.	200–400 °C.	400–550 °C.	30–400 °C.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*				
114	50	20	30	$MgO\ Al_2O_3\ 6SiO_2$	.....	19.45	9.35	5.52	13.99
116	50	30	20	$MgO\ Al_2O_3\ 2SiO_2$	.....	7.34	6.11	4.68	6.68
117	50	20	30	$MgO\ Al_2O_3\ 2SiO_2$	.....	8.93	4.43	4.05	6.51
119	50	30	20	$MgO\ Al_2O_3\ 4SiO_2$	.....	19.61	11.13	8.08	15.03
120	50	20	30	$MgO\ Al_2O_3\ 4SiO_2$	.....	10.45	5.43	4.45	7.74
152	40	.....	20	$MgO\ Al_2O_3\ 4SiO_2$	40	3.36	4.19	4.78	3.81

It is at once evident from a comparison of these figures that the thermal expansion of these magnesia porcelains increases with the silica content of the body, and, at the same time, is subject to decided variation within the temperature limits of 30°–550° C. On the other hand the porcelain in which the clay content is lower, and all the quartz has been replaced by sillimanite, shows both the lowest thermal expansion and the least variation in the value of the coefficient. However, the composition is not the only determining factor, and the importance of the microstructure must be realized.

CONCLUSIONS.

The work, the results of which have been given, has been successful in showing: First, the injurious qualities imparted to electrical porcelains by the use of feldspar as a flux; and second, in bringing out the desirability of replacing the quartz by minerals or synthetically prepared materials which are more constant in volume when heated. The remedial procedures advocated are, hence: (1) The replacement of feldspar by other fluxes, such as silicates of the type $MgO\ Al_2O_3\ 2SiO_2$, or $MgO\ Al_2O_3\ 4SiO_2$, or other silicates of beryllium and the alkaline earths, either natural or prepared artificially. (2) The elimination of quartz and the substitution of substances not subject to inversions or other volume changes. These may be highly calcined kaolin, alumina, zircon, or sillimanite, either natural or produced synthetically.

The compositions of the most typical porcelains produced in this work are compiled in Tables IV, V, and VI, and the T_e value is given for each body, so that these tabulations may be consulted for detailed information.

All of the electrical measurements, as well as the determinations of the thermal expansion of the porcelains, have been made in the Washington laboratories of the Bureau of Standards.

TABLE IV.

Number of body.	16	17	18	22	23	24	28	32	35	36	39	40
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Kaolin	45.00	45.00	45.00	45.00	45.00	50.00	50.00	55.00	55.00	55.00	55.00	60.00
Feldspar	16.00	18.00	20.00	28.00	30.00	16.00	24.00	14.50	20.50	22.50	28.50	16.00
Potters flint	39.00	37.00	35.00	27.00	25.00	34.00	26.00	29.00	23.00	21.00	15.00	24.00
Whiting ($CaCo_3$)	.....	.....	.....	.....	.....	.....	.....	1.50	1.50	1.50	1.50	.....
Ball clay	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcined kaolin	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcine No. 3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcine No. 19	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcine No. 20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Maturing temperature in cones	16	15	14	14	13	15	14	14	12	12	12	13
T_e value	560	390	440	370	450	380	358	400	460	400	390	410

Number of body.	47	48	49	50	55	63	70	72	73	74	77	78	79
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Kaolin	60.00	50.00	50.00	51.00	50.00	50.00	50.00	37.00	37.00	.....	5.00	10.00	10.00
Feldspar	30.00	24.00	22.00	25.00	28.50	13.50	16.40	22.00	17.60	.....	.....	.....	.....
Potters flint	10.00	5.00	12.00	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Whiting ($CaCo_3$)	.....	1.00	1.00	1.50	1.50	1.50	1.00	.....	.....	.....	.....	.....	.....
Ball clay	.....	.....	.....	.....	.....	.....	.....	5.00	5.00	15.00	10.00	10.00	15.00
Calcined kaolin	.....	20.00	15.00	.....	20.00	35.00	.....	.....	.....	.....	.....	.....	.....
Calcine No. 3	.....	.....	.....	.....	.....	.....	4.10	.....	4.40	.....	.....	.....	.....
Calcine No. 19	.....	.....	.....	22.50	.....	.....	28.50	.....	.....	.....	.....	.....	.....
Calcine No. 20	.....	.....	.....	.....	.....	.....	.....	.....	.....	85.00	85.00	80.00	75.00
Zircon	.....	.....	.....	.....	.....	.....	.....	36.00	36.00	.....	.....	.....	.....
Maturing temperature in cones	10	14	14	14	14	16	14	13	13	13	13	13	13
T_e value	400	410	400	390	400	540	460	500	450	640	800	790	640

Number of body.	88	94	95	107	109	116	152	180	193	194	195
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
Kaolin	50.00	45.00	40.00	47.00	25.00	50.00	30.00	69.00	40.00	40.00	40.00
Feldspar	8.00	17.60	.....	14.00	.....	.....	.....	.....	.....	.....	.....
Potter's Flint	30.00	.....	42.00	21.00	.....	30.00	.....	5.75	25.00	15.00	5.00
Magnesium carbonate	.....	.....	.....	10.00	.....	.....	.....	4.58	.....	.....	.....
Ball clay	.....	.....	.....	8.00	20.00	.....	10.00	9.15	10.00	10.00	10.00
Calcine kaolin	.....	.....	.....	.....	35.00	.....	.....	.....	.....	.....	.....
Calcine No. 8A	.....	.....	.....	.....	20.00	.....	.....	.....	.....	.....	.....
Calcine No. 13	12.00	4.40	.....	.....	.....	20.00	.....	.....	.....	.....	.....
Calcine No. 14	.....	.....	18.00	.....	.....	.....	20.00	.....	.....	.....	.....
Calcine No. 19	.....	.....	.....	.....	.....	.....	40.00	.....	.....	.....	.....
Calcine No. 20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Calcine Al_2O_3	.....	33.00	.....	.....	.....	.....	.....	11.52	.....	.....	.....
Beryl	.....	.....	.....	.....	.....	.....	.....	.....	25.00	35.00	45.00
Maturing temperature in cones	15	16	20	12	16	18	16	20	12	11	11
T_e value	590	620	630	480	610	730	690	640	.....	.....	.....

TABLE VI.—*Compositions of calcines.*

Calcine No.	$MgCo_3$.	Kaolins.	Flint.	Calcined Al_2O_3.	Boric acid.	Calcination temperature cone.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	
3	39.50	60.50	.....	.....	.....	10
8–A	14.40	44.30	41.30	.....	.....	12
13	23.85	76.15	.....	.....	.....	12
14	18.20	56.00	25.80	.....	.....	13
19	.....	70.20	.....	27.80	2.00	20
20	34.30	.....	65.70	.....	.....	16

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REPORT No. 53.

PART IV.

CEMENTS FOR SPARK-PLUG ELECTRODES.

By H. F. Staley.

RÉSUMÉ.

Considerable trouble has been caused in airplane engine work through the breaking of the central electrode of spark plugs.

An investigation of this problem by the Bureau of Standards shows that in many cases the cement used to hold the nickel electrode wire in the porcelain is of such a nature that it rapidly eats away the wire through oxidization, when exposed to the high temperature of the engine cylinder. A cement composed of silicate of soda and raw kaolin has been found to give the least trouble in this respect.

In cases where the cement holds the wire firmly in the porcelain the latter often cracks when subjected to heat due to the difference in the coefficients of thermal expansion of the wire and the porcelain. The breaking of the porcelain does not seem to be due to leaky spark plugs as has often been supposed to be the case.

On account of the difficulties attending the use of any form of cement between the porcelain and central electrode, the elimination of the cement and the use of a mechanical seal at the top of the porcelain is greatly to be desired. In such a plug only a porcelain strong enough to safely withstand the resulting stresses should be used. The porcelain recently developed by the Bureau of Standards is believed to meet these requirements.

CEMENTS FOR SPARK-PLUG ELECTRODES.

Considerable trouble has been experienced in the operation of airplane engines due to breaking of the central electrode wires in spark plugs at the point where they enter the porcelain.

Examination of numerous broken spark plugs showed that at the point of failure the central electrode wire was oxidized practically through its cross section, this oxidization extending up into the spark plug a variable distance, depending upon the permeability of the cement with which the wire was surrounded. In some cases the cement had melted and run down along the wire. It was apparent from the nature of the failures that in order to thoroughly study the problem, the composition of the electrode wire, porcelain insulator and the cement used to secure the wire to the insulator, must be investigated.

The material in common use for central electrodes in the spark plugs bought by the Government for airplane service is known as "97 per cent spark point nickel wire." The following are typical analyses:

Analyses of wire.

Laboratory No	47134	47135
Nickel	97.0%	96.9%
Manganese	1.5	1.6
Iron	0.8	0.9
Copper	0.4	0.2

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 35.

Thermal expansion of wire.

Interval:	Average coefficient.
25 to 200° C	14×10^{-6}
200 to 400° C	16
400 to 600° C	16
600 to 840° C	20
25 to 840° C	17

In the composition of porcelain insulators several spark-plug manufacturers use modifications of Bureau of Standards body No. 152, the thermal expansion of which is as follows:

Thermal expansion of porcelain.

Interval:	Average coefficient.
30 to 200° C	3.36×10^{-6}
200 to 400° C	4.19
400 to 520° C	4.78
30 to 400° C	3.81
30 to 510° C	4.06

In the case of the cements used between the wire and porcelain, it developed that most of these consisted of a mixture of silicate of soda with finely powdered solids, which were supposed to be chemically inert. Barium sulphate was the solid used by the manufacturer whose plugs gave the most trouble, while another maker, whose plugs are used in large quantities for airplane work, employed finely ground silica. Silicate of soda cements are advantageous for this work because they are cheap, can be worked cold, and are gas tight at low temperatures.

To determine the effect of various cements on electrode wires, mixtures were made of silicate of soda and typical powdered materials. Small pellets of these mixtures were worked around commercial nickel electrode wires and after drying at 120° C., the wires and adhering pellets were heated in an oxidizing atmosphere to 1,000° C., which approximates the temperature at the tip of the porcelain in an airplane engine in operation. After cooling, the pellets were broken off and the wire beneath them examined. The results are given in Table I.

From Table I, it appears that the solids used do not act simply as inert material. In the second case in this table, for instance, the reaction probably is as follows:

$$Na_2O\cdot SiO_2+BaSO_4=Na_2SO_4+BaO\cdot SiO_2.$$

The reactions in the other cases are too problematical to be worth discussion here. It is sufficient to say that raw kaolin was found to be the best solid for use in spark plug cements since it absorbed the sodium silicate as fast as it melted and produced an impervious mass. The oxidation is greatly accelerated by contact with fused alkaline substances.

Attempts were made to seal the wires into the porcelain after heating by means of glasses ranging in coefficient of thermal expansion from that of the porcelain to that of the wire. None of these attempts have so far been successful, for in cooling, the glass pulled away either from the porcelain or from the wire. Special wire, with a coefficient of thermal expansion about equal to that of porcelain, has been ordered. These experiments will then be repeated.

As a part of this investigation, a visit was made by a representative of the bureau to a spark plug factory where all porcelains were subjected to a sudden heating test, in which the tip of the porcelain was placed in the flame of a Meker burner. The porcelains were uniformly passing this test. When it was suggested that porcelains containing electrodes be tested in the same manner, it was found that 45 per cent of the porcelains cracked. As the result of actual engine tests of complete plugs at the bureau, it has been found in general that in the cracked plugs the cement is holding well, the failure being due to the difference in coefficient of thermal expansion between the porcelain and nickel wire, which sets up so high a stress between the two parts of the plug that one or the other has to give way. This conclusion is confirmed by the fact that in the above factory tests, on the 55 per cent of plugs that did not fail, either cement was absent from around the wire near the tip of the porcelain or else it softened and gushed out of the hole.

The subject of gas leakage of spark plugs in relation to failure of the central electrode has also been studied. While considerable work has been done in determining the gas leakage of new plugs in view of the above results, it appeared advisable to determine leakage on plugs that had been used in an airplane engine. In Table 2 are given the results of examination of a typical lot of 40 plugs. The following information will be of assistance in reading this table. Of the 12 broken plugs, 6 leaked badly and 6 did not leak at all. Of those that leaked badly, 4 contained loose wires and, in the case of one of these, the wire could be pulled out easily. It is evident that tests for gas leakage on new plugs give no indication of their gas leakage in use and that this leakage does not necessarily produce broken porcelains.

In conclusion it may be stated that on account of the difficulties incident to the use of cement between the electrode wires and porcelains in spark plugs, the elimination of the cement entirely and the use of a mechanical seal at the top of the porcelain is greatly to be desired. The mechanical stress incident to the use of such seals should be localized at the top of the plug. The type of porcelain developed by the bureau has sufficient strength to withstand the necessary stresses. At least two manufacturers of spark plugs are following up the suggestions of the bureau along this line and tests of these plugs are to be carried out as soon as samples are received.

TABLE I.—*Effect of cements on electrode wires.*

Cement No.	Sodium silicate 40° Bé., c. c.	Water, c. c.	Solid.		Effect of heating to 1,000° C.	
			Grams.	Kind.	Oxidation of wire.	Description of cement.
1	5	5	30	Powdered silica	Very bad	Hard, strong, slightly porous. Part of material had run down the wire.
2	10		30	do	do	Do.
3	5	2		Barium sulphate	Eaten through	Part of material had melted and run down wire, leaving a hard blue mass behind.
4	7			do	do	Do.
5	5	5	30	do	None	Hard, strong, very slightly porous.
6	10		30	do	do	Hard, strong, not porous.
7	5	9	15	Kaolin	Very bad	Soft, weak, porous.
			15	Al. oxide		
8	10	4	15	Kaolin	do	Do.
			15	Al. oxide		
9	5	13	30	do	do	Soft powdery mass.
10	10	8	30	do	do	Do.
11	10	8	30	Kaolin calcined at 500° C	do	Hard, weak, porous.
12	10	16	30	Kaolin calcined at 750° C	do	Do.
13	10	14	30	Kaolin calcined at 1,000° C	do	Soft weak, porous.
14	10	12	30	Kaolin calcined at 1,250° C	do	Medium, hard, weak, porous.
15	Wire dipped in 40° Bé. sodium silicate				do	
16	Clean wire				Slight	

TABLE 2.—*Gas leakage around electrode wires in spark plugs that had been used for 1¾ hours in a Liberty engine.*

Porcelain broken.	Porcelain not broken.	Leakage bad.	Leakage moderate.	No leakage.	Wire loose.	Wire easily pulled out.
12		[1] 6			4	1
				6		
	28	17			12	9
			8		3	2
				3		
Total 12	28	23	8	9	19	12

[1] Part of these may have been broken while the plugs were being removed from the engines.

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REPORT No. 54

EFFECT OF TEMPERATURE AND PRESSURE ON THE SPARKING VOLTAGE

BY

L. B. LOEB and F. B. SILSBEE

Bureau of Standards, Washington, D. C.

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REPORT No. 54.

EFFECT OF TEMPERATURE AND PRESSURE ON THE SPARKING VOLTAGE.[1]

By L. B. Loeb and F. B. Silsbee.

RÉSUMÉ.

The investigation described in this report was conducted at the Bureau of Standards for the National Advisory Committee for Aeronautics.

The spark discharge used to fire an internal combustion engine must pass through the compressed and heated mixture which occupies the engine cylinder near the end of the compression stroke. The object of the experiments described in this report was to determine how the voltage necessary to produce such a spark discharge varies with the pressure and temperature of the gas. The results are of value in showing what voltage an ignition system is required to deliver in order to produce a spark and in enabling one to set up in the laboratory a convenient experimental gap electrically equivalent to that in the engine cylinder.

Measurements were made on spark plugs screwed into a bomb containing compressed air, and inserted in an electric furnace so that both pressure and temperature could be varied as desired. The sparking voltages were measured on four plugs, having different electrodes, at pressures up to 100 pounds per square inch and temperatures up to 500° C. Both 60-cycle alternating current and current obtained from a magneto were used. The observed voltages are plotted against pressure in plots 2, 3, 4, and 7, and against density in plot 5.

The results show that the sparking voltage is a linear function of the density of the gas and depends upon pressure and temperature only as they affect the density, i. e., heating a gas at constant volume does not affect the sparking voltage. For a typical spark plug gap set at 0.5 mm. (0.020 inch) the sparking voltage was found to be 2,800 volts at atmospheric density and 9,400 volts at a density five times as great.

The data given in this report were obtained on air only. The results of measurements made elsewhere indicate that the sparking voltage in an explosive mixture of gasoline and air is about 10 per cent less than in pure air, and that the change in voltage is proportional to the amount of gasoline present.

INTRODUCTION.

This report describes some experiments made to determine the change of spark potential with pressure and temperature, in order to determine the necessary minimum potential for causing sparks to pass in a gasoline engine whose compression ratio was known and in which the temperature of the gases before ignition could be estimated.

According to the simple theory (J. J. Thomson, Conduction of Electricity through Gases; Townsend, Electricity in Gases; and Peek, Transactions of the American Institute of Electrical Engineers, 1910–1916) the sparking potential depends solely on the density of the gas between the electrodes for a given fixed pair of electrodes, i. e., on the total number of molecules between the electrodes. This has been investigated over a considerable range of pressures, spark distances, and forms of electrodes by numerous observers, but only three investigators have studied the effect of temperature, and then only over a limited range. They all found that the sparking potential depended solely on the density of the gas over the range studied.

In the study of airplane spark plugs it seemed advisable to determine whether this law held for pressures and temperatures which might occur in the cylinders of a high compression engine

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 14.

just before the ignition of the charge. In airplane engines the maximum compression pressures under normal conditions range from 90 to 130 pounds per square inch with temperatures up to 300° C.

APPARATUS.

The experiments were conducted as follows: An ordinary ⅞-inch Titan A. C. porcelain plug was screwed into a steel bomb about 25 cm. (10 inches) long, having the design indicated in figure 1. There was a thick glass window opposite the sparking terminals when the plug was screwed in position. A high-pressure air tank connected to the bomb through suitable valves served to regulate the air pressure to any desired value. Temperatures were measured by a Pt, Pt–Rh thermocouple, B. S. W5, which was inserted in a steel tube sealed at one end with walls ½ mm. (0.020 inch) thick. This was screwed into the bomb so that its inner end was within 1 cm. of the sparking terminals of the plug. The bomb was placed in a cylindrical electric resistance furnace and packed with asbestos wool, so that only the porcelain insulator was exposed at one end, while the window projected out about 5 cm. (2 inches) beyond the other end.

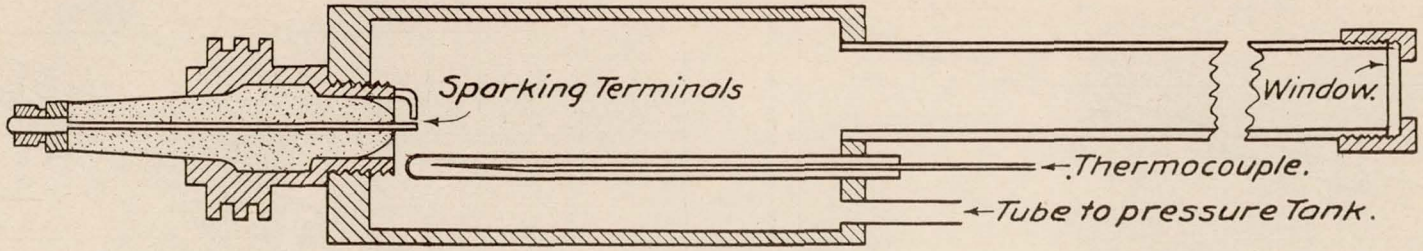
Sixty-cycle voltage was supplied through a step-up transformer having a ratio of 200:1 and applied between the central electrode and the bomb. A resistance of 220,000 ohms was put in series with the plug to avoid an excessive current and consequent burning of the terminals when the spark passed. The voltage was read on a voltmeter connected to the low-tension side of an auxiliary step-down transformer. The passage of the spark was made evident both by the kick of the voltmeter and by the appearance of the spark in the bomb. Ionization was provided for by the use of a half milligram sample of radium in most of the experiments, while in some a 50-mgm. sample, placed just below the electric furnace, was also used. This ionization served to eliminate the complicating effect of spark "lag" and made the readings much more consistent and reliable. No striking difference in the readings could be noticed with the two different samples.

The tests were run on three Titan plugs: No. 1 had the regular terminals of Ni–Mn wire 1.3 mm. (0.051 inch) in diameter set at right angles and separated by 1.8 mm. (0.071 inch); No. 2 was a Titan plug with similar terminals 3.13 mm. (0.123 inch) in diameter rounded at the ends, separated by 1.2 mm. (0.047 inch); No. 3 was a plug like No. 1 but with a distance of 2.2 mm. (0.086 inch) between the wires. In each case the spark passed between the cylindrical surfaces of the wires near the point of closest proximity.

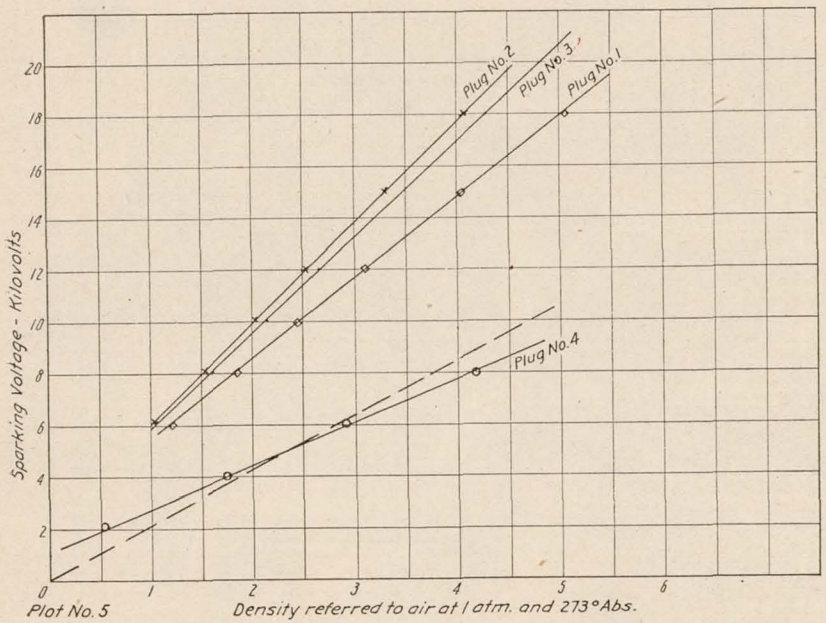
PROCEDURE.

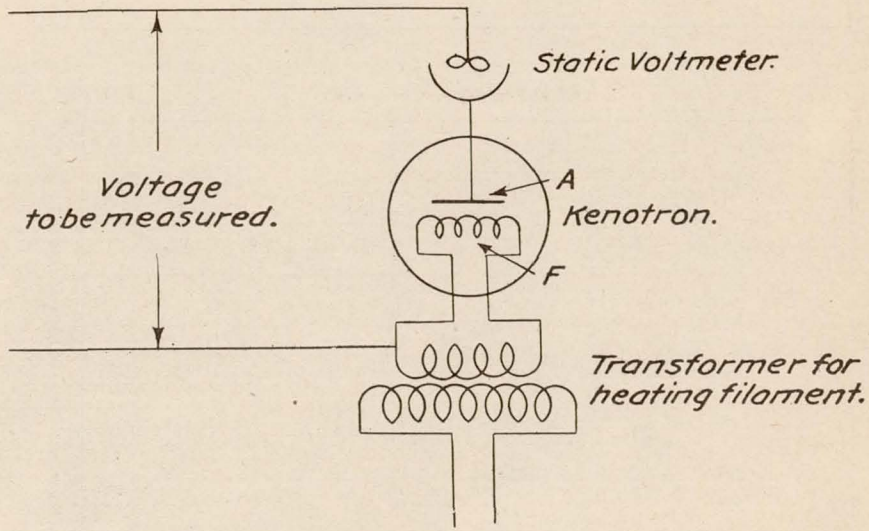
The readings were taken as follows: The temperature was run up to the desired value and held constant from 15 minutes to half an hour. There were fluctuations at the higher temperatures of as much as 10 degrees either way so that a mean temperature was chosen as representing the true conditions. The breakdown voltage of the gap was then determined by at least 10 trials for each pressure. The pressure was increased in steps of 10 pounds per square inch. The pressures were read by two small pressure gauges whose ranges were from 0 to 100 pounds per square inch. The spark potentials were read to as high a pressure as it was possible to obtain without the sparks passing over the outside of the insulator. Then the pressure was reduced in steps of 20 pounds and readings again made. As a whole the return readings checked the first readings well. This can be seen from the plots where maximum sparking voltage is plotted against the pressure for each temperature. As the voltage which could be used without sparking over the outside of the porcelain was about 19,000 volts, no voltages were measured above this. The pressure range over which the measurements could be carried out started from 60 pounds at room temperature and increased until at 200° C., or thereabouts, pressures of 100 pounds could be used.

From then on the pressures were limited with increasing temperatures by a new phenomenon which may have been caused by electron emission from the hot terminals at high voltage. Under these conditions the spark was replaced by a sort of purple brush discharge (corona) which came on gradually as the voltage was increased.

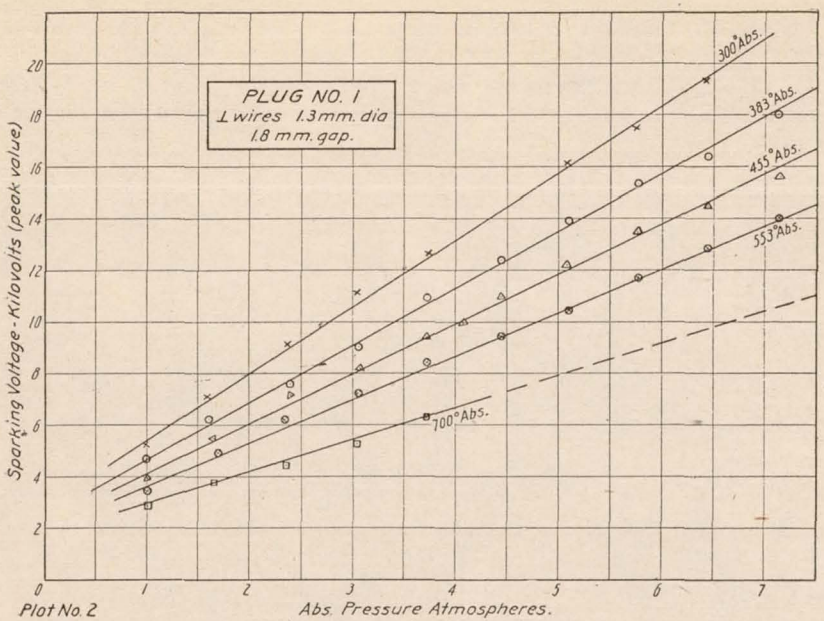


SPARK PLUG BOMB.
Fig No. 1

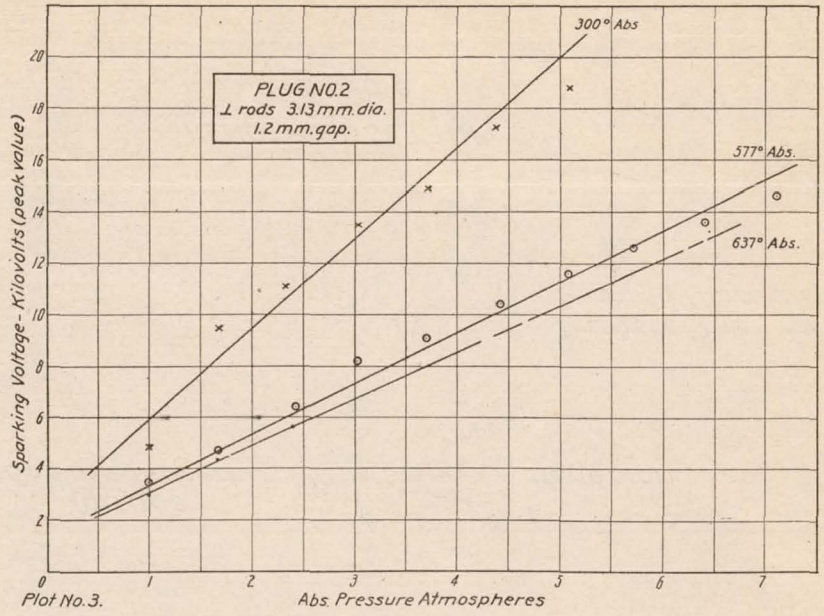




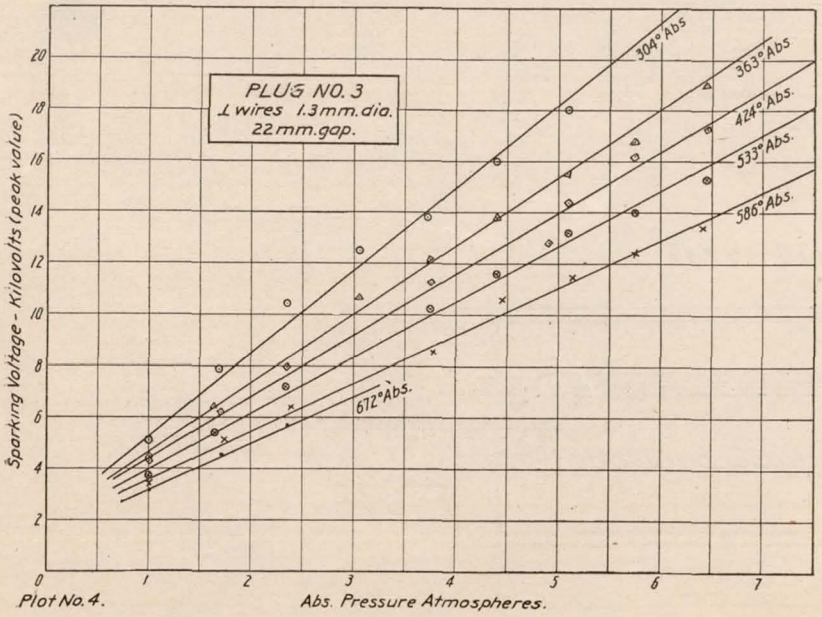
KENOTRON SET-UP.
Fig No. 6



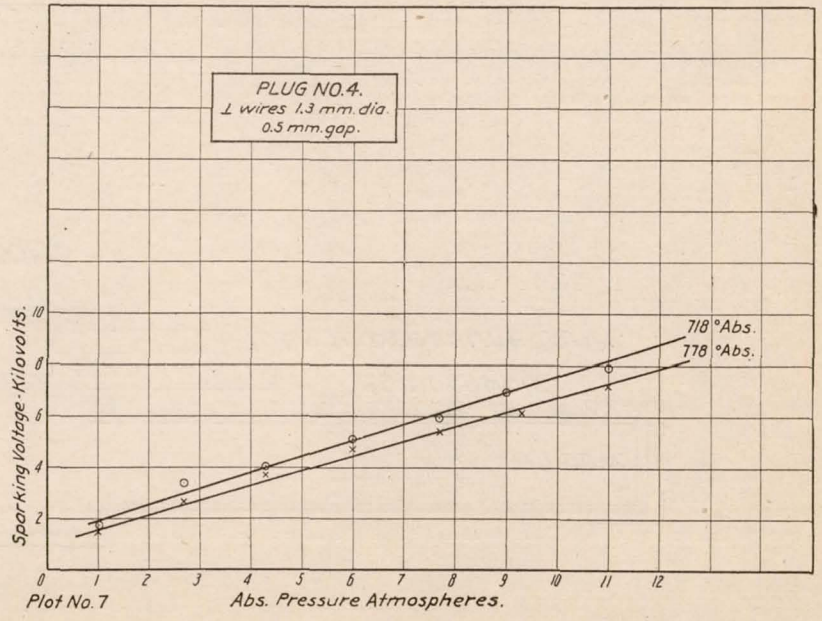
Plot No. 2



Plot No. 3.



Plot No. 4.



Plot No. 7

It was at first thought that this glow discharge might be an important factor in causing ignition trouble. Further measurements were therefore made in the same apparatus but with a Bosch D–6 magneto as a source of voltage. With this arrangement no brush discharge could be detected although the observations were carried to 760° C. Above 600° C. the electrical conductivity of the porcelain insulator was great enough to prevent the magneto from sparking at the higher pressures, but there was no sign of brush discharge under any conditions. It is probable that a certain time is required for such a discharge to form and that the very sudden application of voltage produced by the magneto does not admit of this.

RESULTS.

The curves plotted between maximum sparking potentials in kilovolts and pressure in atmospheres may be seen in plots 2, 3, and 4. The results represented by all these curves, except the one for low temperature measurement with the larger terminals could be repeated consistently. It is possible that a stronger source of ionization should have been provided, and the voltage increased still more slowly in this case. The slight curvatures of the lines may be due in part to the gauges, since no calibration corrections were applied. The direction of the curvature is the same as that noted by other observers.

The data given in the curves were analyzed by first reading from each of the curves the pressure corresponding to a given voltage, say 10,000 volts. From this pressure and the temperature pertaining to the curve, the relative density of the gas is then computed by the formula:

$$\rho = \frac{\delta}{\delta_0} = 273\frac{P}{T}$$

where δ_0 is the density at 1 atmosphere and 273° absolute, P is the pressure in atmospheres, and T the absolute temperature in degrees centigrade. This was done for six different voltages on each plug. Table I gives the results on plug No. 1 at 10,000 and 8,000 volts, and is typical of the other data. It is evident that the densitites thus obtained are constant within a few per cent over the entire range and show no systematic change with temperature or pressures.

TABLE I.

Temperature Abs.	Density at	
	10,000 volts.	8,000 volts.
300°	2.51	1.83
383°	2.46	1.80
455°	2.27	1.80
553°	2.38	1.78
700°	2.59	1.96
Mean	2.45	1.83

It may therefore be concluded that the breakdown voltage is a function of the gas density only. To determine the form of this function the average values of density obtained as described above are plotted against the corresponding voltage in plot 5. The curves thus obtained show that the breakdown voltage is a linear function of the density but is not proportional to it. The data can be represented by the following equations:

Plug No. 1	$E = 2.2 + 3.1\ \rho$
Plug No. 2	$E = 1.8 + 4.0\ \rho$
Plug No. 3	$E = 2.4 + 3.4\ \rho$

Where E is the sparking voltage in kilovolts and ρ is the density relative to air at atmospheric pressure and 0° C. The constants in these equations are of course dependent upon the shape and spacing of the electrodes, and would be smaller for the case of the shorter 0.5mm (0.020 inch) gaps used in spark plugs.

In addition to the measurements with alternating current described above, a second series of tests was made, using a Bosch D–6 magneto as the source of e. m. f. and a special crest voltmeter equipment[1] to measure the breakdown voltage.

This equipment consisted of an Albrecht electrostatic voltmeter connected in series with a G. E. kenotron (electric valve) as shown in figure 6. This valve permits current to flow when the heated filament F is negative with respect to the relatively cold anode A, but allows no current to flow in the reverse direction. Consequently, a negative charge accumulates on the insulated conductor, formed by the anode and the case of the electrometer, of such amount that when the sparking electrode and voltmeter needle are at their greatest positive potential the filament and anode are at the same potential, and there is no tendency for further charging. During the rest of the time the needle of the voltmeter is near ground potential, but the rectifying effect of the kenotron prevents the charge from leaking off. Consequently the meter comes to a steady deflection which measures the maximum positive voltage applied.

Runs were made with this apparatus at temperatures of 460° C. and 520° C. up to pressures of 150 pounds per square inch, using a Champion (Toledo) plug No. 4 with X-bend electrodes set with the usual spacing of 0.5 mm. (0.020 inch). The results as obtained are plotted in plot 7 and the combined data from these curves are plotted against relative density in plot 5, giving a line whose equation is

$$E=1.1+1.7\rho.$$

These measurements with the magneto and crest voltmeter showed the presence of a further complication due to the fact that the heat of the spark raised the temperature of the electrodes very materially. This in turn heated the gas near them so that the discharge occurred through gas which was decidedly less dense than the surrounding atmosphere. This was indicated by the fact that at first starting the magneto the voltmeter showed a relatively high voltage (in one case 4,100 volts), which decreased gradually for nearly a minute, after which it remained constant at a much lower value (2,350 volts). The time required for the change implies very strongly that it is a purely thermal effect rather than any ionization due to the preceding sparks, since the latter effect would be almost instantaneous. In the case of a spark plug in an engine cylinder, the central electrode, being insulated thermally as well as electrically by the core, is much hotter than the incoming charge and consequently this effect may be present to some extent.

As a check upon the laboratory data measurements were also made in a Hall-Scott A–5 aviation engine having a compression ratio of 4.2:1. Owing to the late closing of the intake valve and the advance of the spark, the actual ratio of cylinder volume at intake to that at ignition was only 3.2:1. If it can be assumed that the charge in the cylinder is at atmospheric pressure and temperature at the closing of the intake valve, then the relative density at ignition will be 3.2. Plug No. 4 was run in this engine firing from a Dixie "88" magneto. The crest voltage as measured by the kenotron was found to be 5,950 volts. Measurements with a calibrated spark gap having 1 cm. spheres indicated 4,500 volts. The voltage predicted for this density from figure 5 is 6,400 volts.

In comparing these results it must be borne in mind that the crest voltmeter loses its charge very slowly, so that it really indicates the highest peak occurring during two or three minutes preceding the reading. The parallel spark gap, on the other hand, is adjusted to fire about half the time and probably gives more nearly the average crest voltage. It appears, therefore, that the results obtained in the laboratory are in substantial agreement with those found on the engine, and that the linear relation between voltage and density may be safely applied to ignition circuits.

It will be noted that the results shown in plot 5 can be represented roughly by a straight line through the origin, such as is shown dotted, and which indicates a direct proportionality between the sparking voltage and density. This relation will be found useful in cases where the voltage is known at some one density and it is desired to estimate it for another density

[1] Sharp, C. H., Electrical World, 69, p. 556, 1917.

not too widely different. It is unsafe, however, to use this law of direct proportionality to extrapolate over a long range from the sparking voltage at normal atmospheric density to that at a very high density.

CONCLUSIONS.

These experiments confirm the relation that the breakdown voltage of a spark gap depends only upon the density of the gas and varies with pressure and temperature only as they affect the density. This relation is found to be valid up to 800° C. and 8 atmospheres pressure. Both the pressure and temperature of the charge in a gasoline engine increase very greatly during the compression stroke, but the sparking voltage can be computed from the linear relations shown in plot 5 without a knowledge of these variables separately, since the density is determined solely by the original density and the compression ratio. For small changes in density, as between engines of different compression ratios, the assumption that the voltage is proportional to the density may be made.

With the sudden discharge from an ignition coil or magneto a disruptive spark is produced even at temperatures where a 60-cycle voltage would produce a brush discharge.

The voltage required for a spark plug set at 0.5 mm. (0.020 inch) in an aviation engine of moderate compression is of the order of magnitude of 6,000 volts.

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REPORT No. 55

INVESTIGATION OF THE MUFFLING PROBLEM FOR AIRPLANE ENGINES

BY

G. B. UPTON and V. R. GAGE

Cornell University, Ithaca, N. Y.

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REPORT No. 55.

INVESTIGATION OF THE MUFFLING PROBLEM FOR AIRPLANE ENGINES.

By G. B. Upton and V. R. Gage.

The initial perception of the presence of an airplane comes commonly through hearing rather than sight. When near a plane the noise of the unmuffled engine is fairly deafening. If muffling can be contrived without too large a loss of power it will become much easier for the pilot to operate his plane, a cut-out being provided for engine-testing purposes. In civil use of planes, if passengers are to be carried or if planes become numerous, muffling will almost surely be required, as it now is for automobiles, motor boats, and stationary engines. In military use of the planes the advantages to be derived from silent operation, if that is possible, are immensely greater; for example, with night-bombing airplanes.

A preliminary report upon this subject was printed as Report No. 10 of the Second Annual Report of the National Advisory Committee for Aeronautics, 1916, pages 41 to 49; hereinafter referred to as Report No. 10. This report outlined the problem, gave the status of muffling for automobile engines, and gave the beginnings of our experimental work. For the main part of the experimental work, Prof. V. R. Gage has been associated with the initial staff of Profs. H. Diederichs and G. B. Upton.

In the early summer of 1917 the Curtiss engine was taken over by the U. S. A. S. M. A. at Ithaca. A considerable amount of experimental data had already been accumulated. Designs of mufflers had been worked out to be tried upon planes in field work. At this time, however, muffling was much less important than the production of engines and planes, so that field experiments with mufflers were not carried out.

The work has fallen into two divisions: First, the determination of the relation between back pressure in the exhaust line and consequent power loss, for various combinations of speed and throttle positions of the engine. Second, the construction and trial of muffler designs, covering both type and size. The main body of the work has been done on a Curtiss OX eight-cylinder airplane engine, 4 by 5 inches, rated 70 horsepower at 1,200 revolutions per minute. For estimation of the muffling ability and suppression of "bark" of individual exhausts, we have also used an "Ingeco" stationary, single cylinder, 5½ by 10 inch, throttling governed gasoline engine, and occasionally other engines.

On the Curtiss engine the carburetor was a Schebler model L. The throttle control rod was graduated and adapted for duplication of settings by means of a screw setting into holes. Adjustment of needle valve and cams controlling the mixture was once made and was not subsequently changed. The ignition was by Bosch magneto with fixed spark, set in the advanced position by the manufacturer's instructions. This adjustment was never changed. The spark plugs gave trouble and had to be renewed. The engine was started by power from an electric (street car) motor, belted to a pulley which was keyed on the end of the fan dynamometer shaft, on the end away from the engine. The engine was brought to a moderate speed with the magneto short circuited and then ignition was turned on and the belt thrown off the fan dynamometer pulley simultaneously. Cooling water was supplied to the engine from the water mains through the regular circulating pump. The water supply valve was always opened to the same point, which had been found by trial to give slightly more than adequate cooling. It was found that air locks might occur and to detect them separate discharges lines were used, one from each block of cylinders.

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In the determination of power losses due to the mufflers it was desirable that the engine should drive a dynamometer with the same torque-speed characteristics as a propeller. We therefore built a fan dynamometer, copying in detail the dimensions of one at the Automobile Club of America's laboratory at New York City. This design of fan has previously twice been calibrated using cradle dynamometers. The fan has two blades set diametrically opposite. These blades are rectangular plates 14 by 10 inches, with the 10-inch dimension radial. As used, the outside diameter across the blades was 42 inches, requiring 35.4 horsepower at 1,000 revolutions per minute, and for other powers varying with the cube of the speed. This adjustment holds the engine to rated load at rated speed (61.2 horsepower at 1,200 revolutions per minute, 69.1 horsepower at 1,250, 77.8 horsepower at 1,300). Dimensions and calibration of the fan are given more completely in Appendix A.

The determination of the power consumed by the fan depends solely upon the measurement of speed. For the reading of speed we used a Hopkins electrical tachometer, with its dynamo driven directly by the engine crankshaft through a flexible coupling. The tachometer was calibrated several times during the progress of the work, both in place on the engine and on a small high-speed lathe.

To determine the power loss due to back pressure, we put exhaust manifolds on the engine along each block of four cylinders and combined the exhausts in a cross pipe at the rear of the engine, as illustrated in figure 1, a photograph of the set-up. The cross pipe ended in a tee with two valves, one a gate valve for adjustment and the other a quick-opening valve, similar to a "molasses" valve. The second valve was used either entirely open or entirely shut; the change from closed to open and reverse could be made instantly. In running to determine power loss the engine would be set at a given throttle position with the quick-opening valve wide open; then closing that valve the gate valve was set to give a desired back pressure. Runs were then made, alternately, in quick succession, with the quick-opening valve open and shut. In each condition readings were taken of speed and back pressure. The alternation of conditions was repeated several times, until the drop of speed (and power losses) associated with a certain back pressure seemed well determined.

There was one manifold for each block of four cylinders composing one leg of the vee. The back pressures of the two groups of cylinders were read separately and independently. The manometer connections were made in each manifold at a point about 6 inches beyond the last cylinder and the two fittings were identical in construction. The pressure taps were made of small brass rods riveted over inside nearly flush with the manifold, with a lock nut outside the manifold. The openings through the rods were the same and were about $\frac{1}{16}$ inch in diameter. This construction was used in order to minimize as far as possible any errors of pressure due to the effect of velocity and to damp the pulsations of pressure. If any such velocity effects did enter into the observations of pressure they would disappear in the taking of the pressure difference of runs with and without applied back pressure. Taking the pressure readings so close to the engine was intentional; all manifold and piping resistance beyond these taps will be shown in the readings, and it was a matter of interest to discover how serious these losses might be, due to the use of long or improper exhaust piping.

From the pressure taps connection was made through rubber tubing of about $\frac{1}{4}$-inch inside diameter and 6 feet long to mercury manometers. A considerable mass of mercury was used in each manometer to obtain the damping effect of its inertia. Further damping was found necessary and was secured by stuffing the upper ends of the manometer tubes with cotton waste. With the engine running, the back-pressure readings were satisfactorily steady and practically without time lag in shifting from running with and without applied back pressures.

The first series of runs was made to determine the power losses caused by different applied back pressures with the engine under a fixed throttle position, set for normal power and speed. The observations taken are shown in the first four columns of Table I. The other values shown in Table I are the results of computations from the averages of the data.

The true speed, revolutions per minute, is obtained from the tachometer readings by the use of calibrations made before and after groups of tests. The correction factor for the tacho-

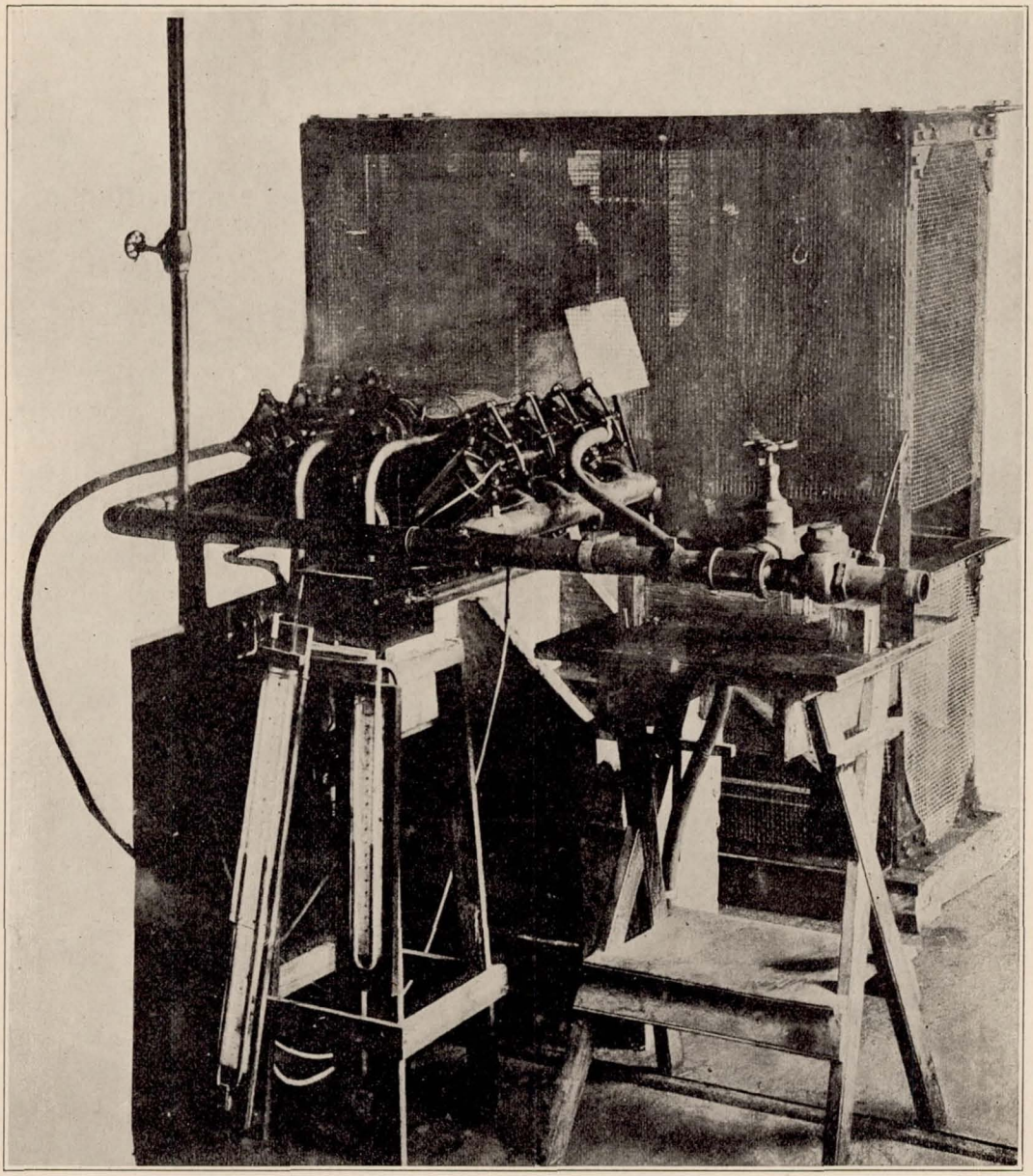


FIG. 1.

meter was always a constant multiplied into the indicated speed. This constant was about 1.09.

The per cent power loss was computed from the relative speeds with and without applied back pressure. If the speed with applied back pressure was 97 per cent of the original speed, the power loss was $(1.00)^3-(0.97)^3=1.00-0.9127=8.7$ per cent. This relation is true because of the loading of the engine by the fan dynamometer. The power absorbed by the fan is proportional to the cube of the speed. (Appendix A.)

The brake M. E. P. (brake mean effective pressure) is the product of the mechanical efficiency of the engine and the mean effective pressure as shown by an indicator diagram, and is expressed in pounds per square inch. For this engine:

Let P = brake M. E. P.
R = r. p. m.
B = cylinder bore diameter, in inches = 4 inches.
S = cylinder stroke, in inches = 5 inches.
N = number of cylinders = 8.
HP = brake horsepower.

Then

$$HP=\frac{P\times\frac{\pi}{4}B^2\times\frac{S}{12}\times\frac{R}{2}\times N}{33000}=\left(\frac{\pi B^2SN}{4\times2\times12\times33000}\right)PR$$

$$=\left(\frac{1}{1577}\right)PR$$

$$P=\frac{(1577)}{R}\times HP.$$

For this fan dynamometer:

$$HP=KR^3$$

in which K is a constant whose value was 35.4×10^{-9} at the setting used. (Appendix A.)

Combining the expressions for this engine and fan:

$$P=\frac{1577}{R}\times KR^3=1577\times KR^2$$

$$=55.8\ R^2\times10^{-6}$$

Various results from this group of tests, as shown in Table I, are shown as curves in plots 2 to 5, inclusive. In all of these curves the abscissa is the applied back pressure measured in inches of mercury. This "applied back pressure" is strictly the increase of manometer reading, over that given with open discharge from exhaust manifolds and piping, with the application of a definite constriction of discharge.

Plot 2 shows the power losses, in per cent, as a function of the applied back pressure. With no applied back pressure the throttle was set and locked to give about 1,230 r. p. m., corresponding to about 65 horsepower output to the dynamometer. The engine did not always come back to this speed and power when the back pressure was relieved, because of many minor variations of ignition, carburetion, lubrication, cooling, etc. These changes were cared for by the method of testing employed, as previously described. The results as to power loss in plot 2 will be found only for one setting of the throttle on this engine. It could not be assumed that the same percentage power loss would be found, for a given applied back pressure, on another engine, or even with other throttle positions on this engine. These power losses are conditioned, also, by the dynamometer characteristic of power varying with cube of speed. They would not hold for automobile engine operation in general, because the load characteristics would be different. This curve is, however, approximately typical, in form and in numerical value, of average flying conditions with airplane motors, when the exhaust is choked by any means to increase the back pressure. This curve gives the information desired concerning the relative magnitude of the power losses incident to increasing the back pressure of an

airplane engine by attempts at muffling. If satisfactory noise suppression can be secured with small increases of back pressure, the power loss may be tolerable.

For moderate back pressures the power loss is substantially proportional to the back pressure. For higher back pressures the power loss mounts rapidly, apparently at such a rate that a back pressure of even less than 10 pounds per square inch (20 inches mercury) would stop the engine. These relations are perhaps better brought out in plot 3, which is the same as plot 2 except that the coordinates are logarithmically scaled. The full line curve in plot 3 is the curve of plot 2 transferred. The dash line in plot 3 shows what would happen if the power loss continued to be proportional to the back pressure.

A possible explanation of this changing effect of back pressure as the back pressure increases may be found by considering the indicator card. This is schematically shown in figure 4. For small back pressures we may expect the main effect to be a lifting of the exhaust line of the card by an amount substantially equal to the increase of back pressure. The result would be a loss of indicated M. E. P. equal to the back pressure, because the elevation of the exhaust line would extend through the whole stroke. The loss of brake M. E. P. will be smaller than the loss of indicated M. E. P. in the ratio of the mechanical efficiency of the engine to unity.

At higher back pressures the exhaust gases are held back in greater amounts in the cylinder, leaving the clearance space, at the end of the exhaust period, filled with an adnormal weight of hot, dead gases. These, reexpanding, interfere with the incoming charge in various ways, lessening the amount of the fuel mixture drawn in. The decrease of charge quantity will result in a decrease of M. E. P. which is added to the decrease of M. E. P. due to lifting of the pressure of the exhaust line.

Probably it is the decrease of charge which is the principal reason for the possibility of stalling the engine by fairly completely choking the exhaust pipe and before complete closure is reached.

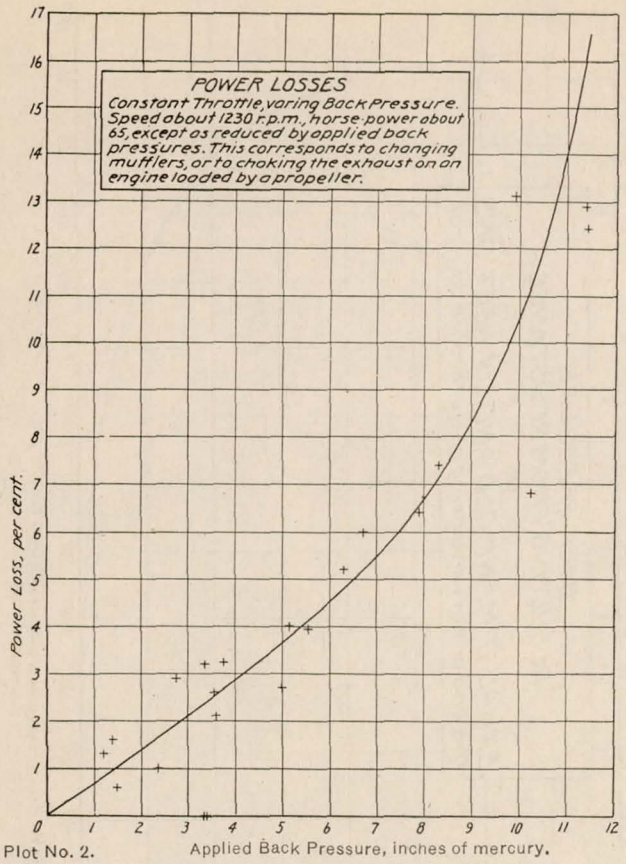
To make the findings of power loss caused by applied back pressure more general, not so much a matter of the particular case studied, the results are given as loss of brake M. E. P., by the curve on plot 5. The previous discussion of the effect of back pressure upon the indicator card explains the form of this curve and the relations between the test curve and the line of equality of brake M. E. P. loss and back-pressure increase. *For the smaller and reasonable values of back pressure it is quite safe to assume that the loss of brake M. E. P. (pounds per square inch) does not exceed, and is nearly equal to, the applied back pressure (in pounds per square inch).* This conclusion is of considerable importance to the designer of engines, exhaust manifolds, and mufflers, and is probably valid for all types and services of internal-combustion engines.

Of interest to the airplane designer is the loss of propeller speed consequent upon back pressure in the engine exhaust. Since propeller speed is tied, in a definite relation, to propeller power, the curve of plot 6 is really another version of plot 2. This curve of plot 6 should correspond approximately to average running conditions of airplane motors. It is about a three-quarter throttle position curve for this engine, and full throttle would probably change the form of the curve only at the higher back pressures.

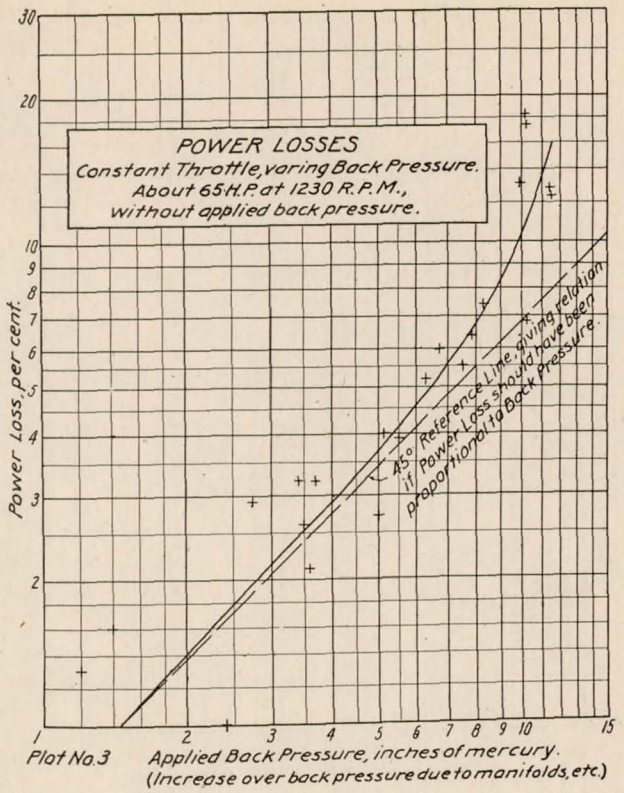
In the second series of tests the engine was brought up to about normal speed and power. The regulating valve at the end of the exhaust pipe was closed, allowing all the exhaust to leak through the joints of the piping and through the walls of the flexible metallic exhaust hose when the end outlet valve was closed. The value of back pressure was purposely made large, in order to give more accurate readings of back pressure, and to see what would happen. Readings of speed and back pressure were then taken with the end outlet valve alternately open and shut, until the values seemed to check among themselves. Then the throttle opening was reduced, and again readings were taken. Immediately after the smallest advisable throttle gun, the normal throttle as used at first was reproduced, and a check run was made.

Table II gives the data and the computations of the runs made on August 24 and 29. The exhaust piping was changed between August 24 and 29 by making the pipe joints tighter.

Plot 7 shows the relation between the brake horsepower and the actual back pressure, as given in Table II. The back pressure increases as some exponential function of the horsepower,



Plot No. 2.



Plot No. 3

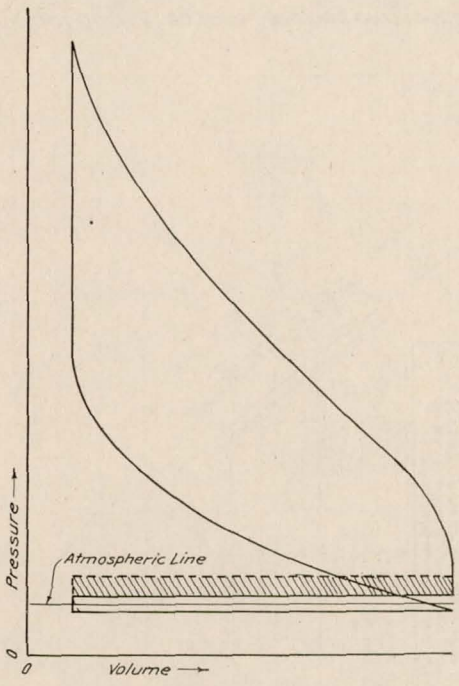
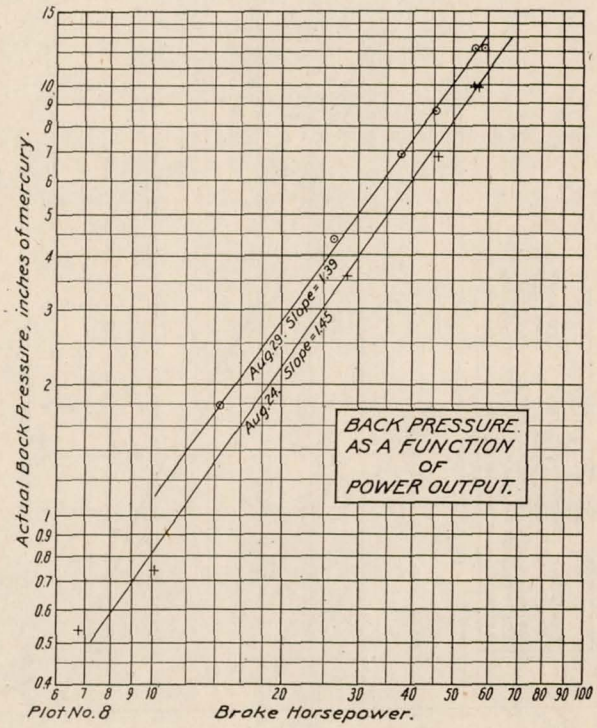
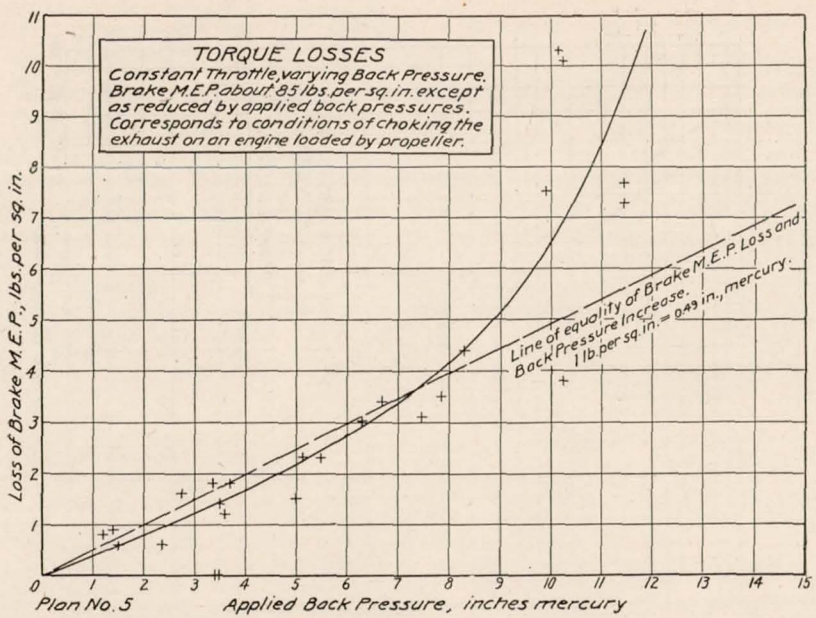
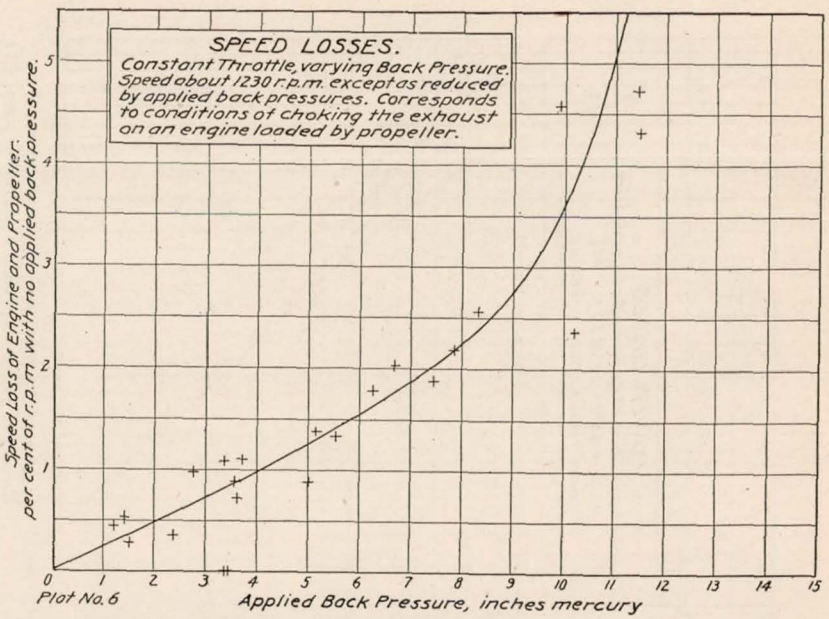


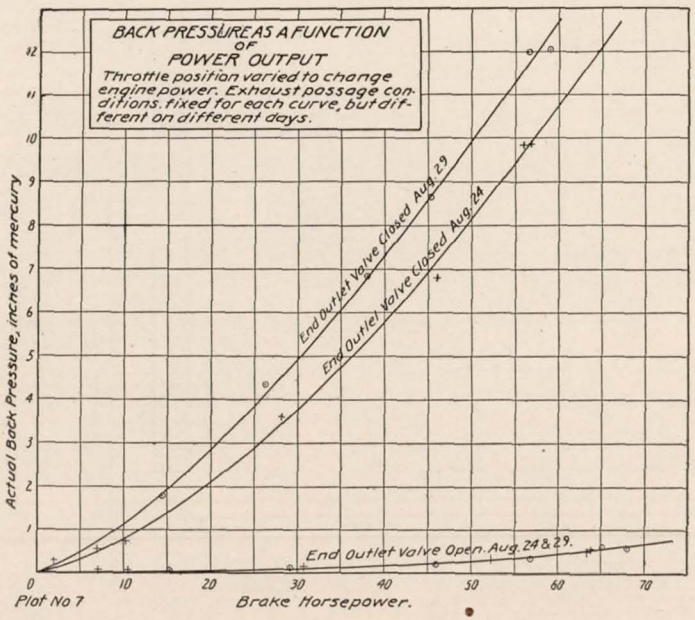
FIG. 4.

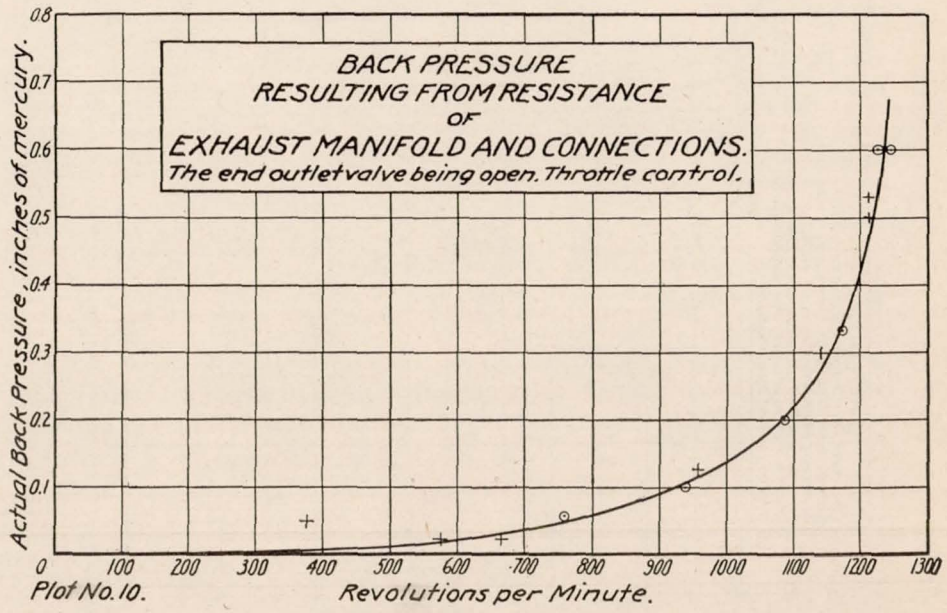


Plot No. 8


TORQUE LOSSES
Constant Throttle, varying Back Pressure.
Brake M.E.P. about 85 lbs. per sq. in. except as reduced by applied back pressures.
Corresponds to conditions of choking the exhaust on an engine loaded by propeller.
Line of equality of Brake M.E.P. Loss and Back Pressure Increase.
1 lb. per sq. in. = 0.49 in., mercury.
Loss of Brake M.E.P., lbs. per sq. in.
Applied Back Pressure, inches mercury
Plan No. 5


SPEED LOSSES.
Constant Throttle, varying Back Pressure.
Speed about 1230 r.p.m. except as reduced by applied back pressures. Corresponds to conditions of choking the exhaust on an engine loaded by propeller.
Speed Loss of Engine and Propeller, per cent of r.p.m. with no applied back pressure.
Applied Back Pressure, inches mercury
Plot No. 6


BACK PRESSURE AS A FUNCTION OF POWER OUTPUT
Throttle position varied to change engine power. Exhaust passage conditions fixed for each curve, but different on different days.
End Outlet Valve Closed Aug. 29
End Outlet Valve Closed Aug. 24
End Outlet Valve Open. Aug. 24 & 29.
Actual Back Pressure, inches of mercury
Brake Horsepower.
Plot No 7


BACK PRESSURE RESULTING FROM RESISTANCE OF EXHAUST MANIFOLD AND CONNECTIONS.
The end outlet valve being open. Throttle control.
Actual Back Pressure, inches of mercury.
Revolutions per Minute.
Plot No. 10.

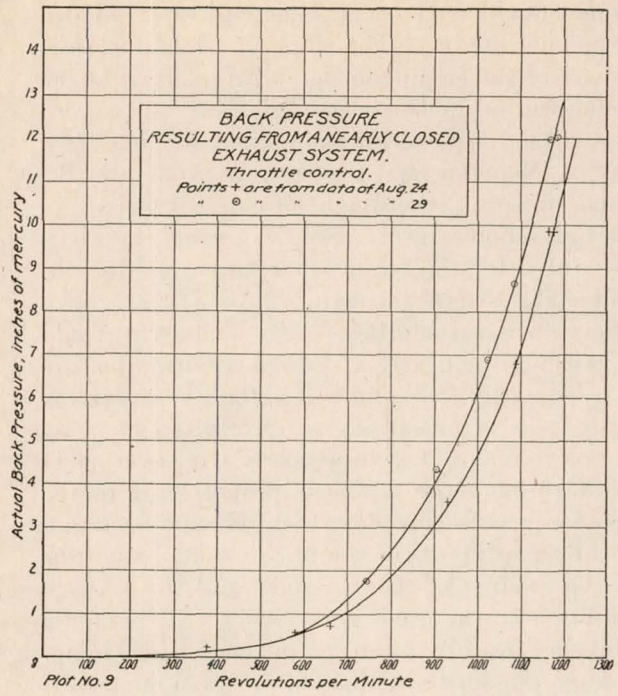
when the conditions of the exhaust passages remain unchanged. The same curves are shown on plot 8, using logarithmic instead of arithmetic coordinates. The slope of these curves is slightly less than 1.5, indicating about the 1.5 power of the engine output. An analysis of the muffler tests made at the University of Michigan (printed in Horseless Age, May, 1915) also indicates that the back pressure varies with about the 1.5 power of the engine output. (An analysis of some of the features of the University of Michigan report is given as Appendix B.)

Neglecting changes of mechanical and thermal efficiency, the weight of exhaust gases, per unit of time, must be nearly proportional to the brake horsepower. So, for a rough approximation, the quantity of exhaust gas can be substituted for the brake horsepower, as abscissæ of the curves, plots 7 and 8. The quantity of fluid discharged through orifices is nearly proportional to the square root of the pressure difference across the orifices. By analogy it would be expected that the slope of the curves on plot 8 should be nearly 2. A contributing feature in the fact that they are not may possibly be explained by the common method of averaging and reading a fluctuating pressure. Averaging in case of pulsations is quite often done by damping. The damping of the oscillations may or it may not give a nearly true average of the pressure. But the instantaneous rate of flow through the orifice is proportional to the square root of the pressure at that instant. So for a pulsating flow there should be found the integration of the product of the average of the square roots of the pressures and the time interval during which the pressures existed, not the product of the square root of the average of the pressures and the total time. The latter method was used, agreeably to the common practice under such circumstances. The flow and the pressure difference in the exhaust manifolds are widely and rapidly pulsating. The average pressure as indicated on the manometer. may be far from the average pressure value which should be used in determining the flow However, when measuring the exhaust back pressures in this conventional manner, the empirical relation here shown may be quite useful—that the back pressure varies approximately as the horsepower of the engine, raised to the 1.5 power.

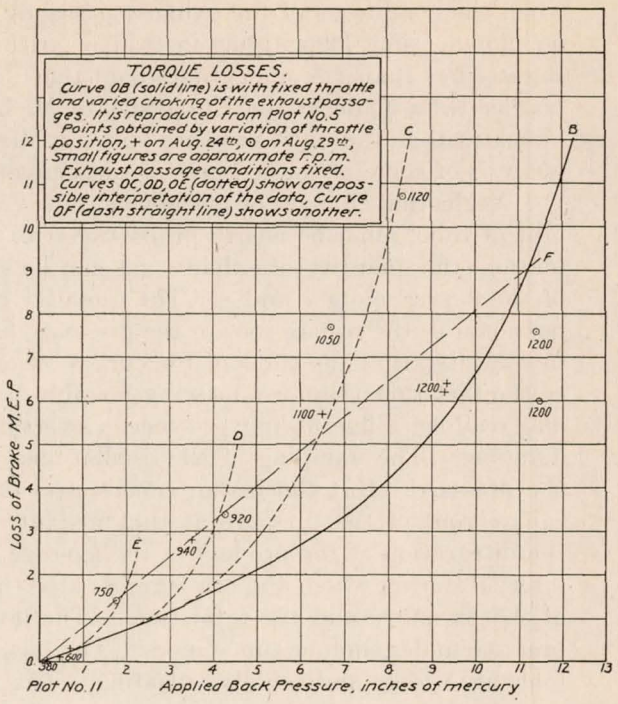
Plots 9 and 10 give information very applicable to muffling of airplane engines. They show how rapidly the back pressure rises to high values as the engine is opened out to full power and speed. The numerical values are obtained from Table II. Plot 9 shows the result of excessive choking of the exhaust which was purposely done in this case to bring out the action. The two curves of plot 9 result from slightly different initial conditions. Plot 10 shows the back pressure due to exhaust piping, only, including sharp turns, some extra pipe resistance, and fittings on our experimental set-up. This curve is of the same type and of the same magnitude of back pressure values which would come from a good muffler. It should be carried in mind that with these figures the engine was driving a fan whose characteristics correspond to an airplane propeller. The form of the curves is conditioned by this type of loading.

In attempting to analyze the data of Table II, reducing the loss of engine torque to terms of brake M. E. P., the result is the "shotgun" diagram of plot 11. Interpretation of this is highly speculative considering the small amount of data which was collected. The analysis here attempted is much broader than the special problem which was being studied, and so no special runs were made to get the information needed to complete this figure. Curve OB is transposed bodily from plot 5, representing runs at fixed throttle and varying exhaust conditions. The straight line OF on plot 11 represents, as near as possible, the average relation from the runs with varying throttle against fixed exhaust conditions. Since the engine was coupled to a fan dynamometer, speed and throttle position are tied together except for the slight modifications due to back pressures, etc. The small numbers adjacent to the points in plot 11 give the approximate r. p. m. of the engine and fan; and equal speeds nearly coincide with equal throttle positions. The apparent scattering of the points may indicate that the points do not belong upon one curve, but upon a family of constant throttle curves such as OC, OD and OE, all similar to OB. The curve OB was at about three-fourths throttle of the engine.

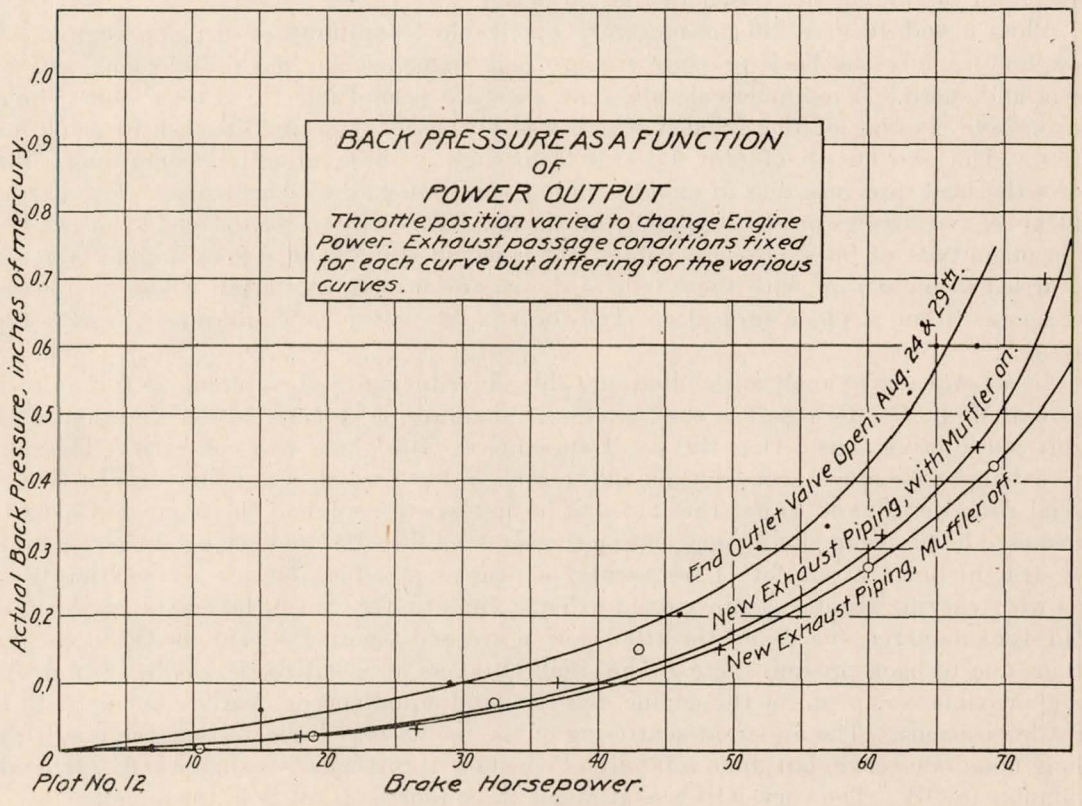
Table III and plot 12 are put in as a demonstration that the choking of the exhaust by sharp turns, pipe fittings, etc., give the same results as choking by a muffler. On August 29,



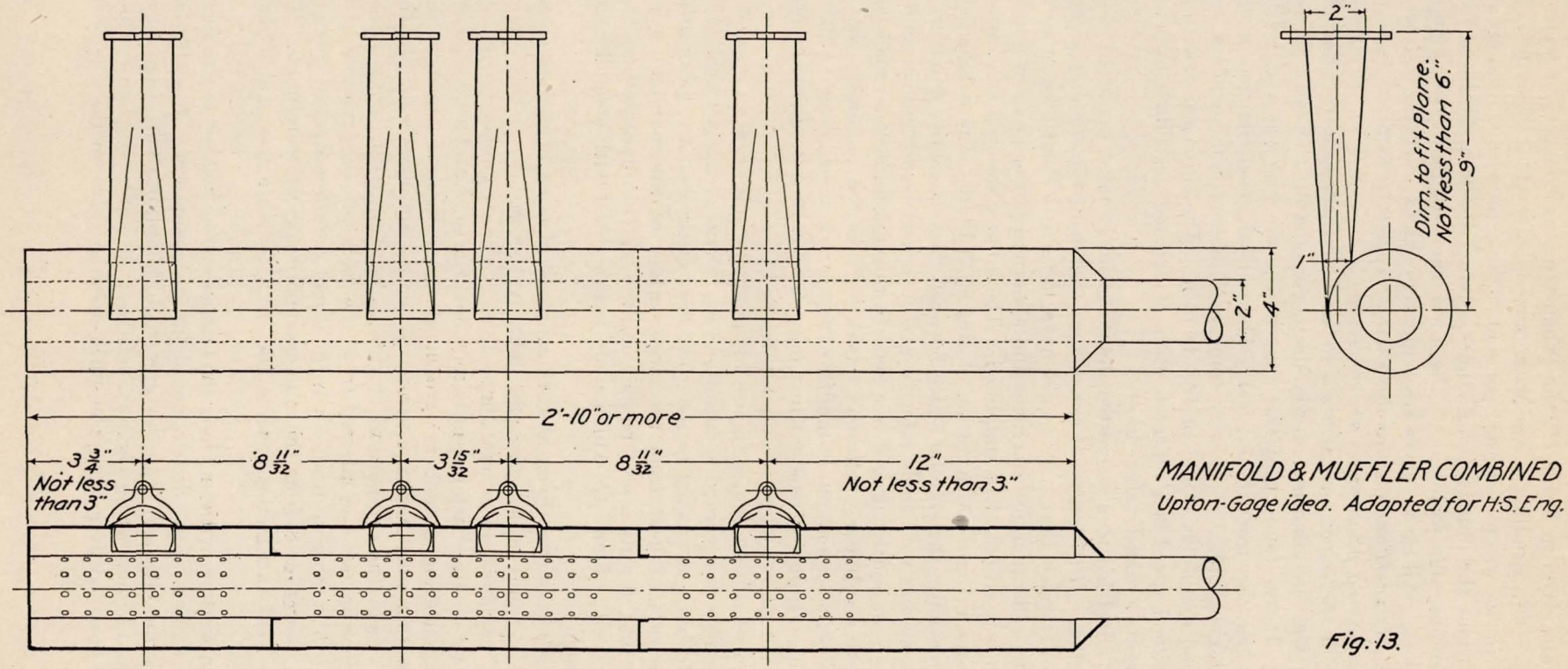
Plot No. 9



Plot No. 11



Plot No. 12



MANIFOLD & MUFFLER COMBINED
Upton-Gage idea. Adapted for H.S. Eng.

Fig. 13.

after taking the data given in Table II, the exhaust piping connections were changed somewhat in order to try out a muffler. The wire-gauze-filled muffler, described on page 48 and figure 4 of Report No. 10, was put on the open end of the exhaust manifold piping. Runs were made with and without the muffler as resistance, giving the data shown in Table III, and in plot 12. This is comparable with plot 7, the lower curve of plot 7 being reproduced as the upper curve of plot 12. All three curves are evidently of the same type. *Hence the information obtained from Tables I and II and their analysis will be applicable to the analysis of muffler actions so far as back pressures and power losses are concerned.*

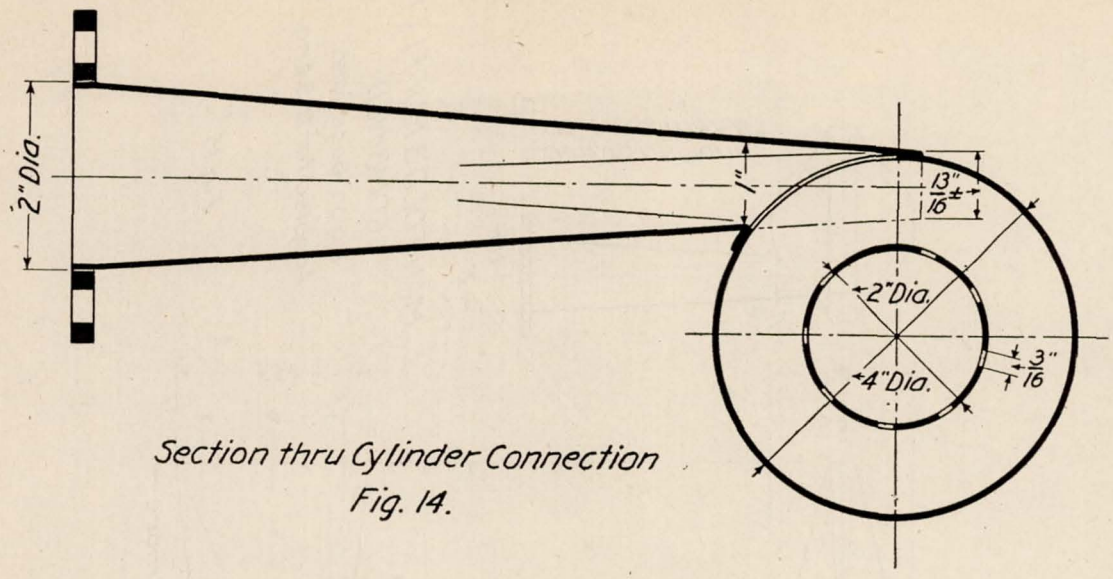
In the course of the experimental work so far described some peculiar phenomena were noted. One such was an abnormal power drop, considering the back pressure, at certain "critical speeds." It was found that this abnormal power loss was avoided by a very small change of speed either way from the critical. The critical speed changed or disappeared with change of exhaust manifold. Apparently some manifolds would not show this phenomena; probably the curved manifolds would be free from it. The supposed cause of this abnormal power loss at a critical speed is a reflected wave of exhaust gas filling the clearance of some cylinder just before its exhaust valve closes.

Study of this effect led to a suggested design of an exhaust manifold, and ultimately to the design of a muffler. If the pulses of exhaust gas, following the opening of successive exhaust valves, could be so trapped that they would never return to their own or other cylinders by direct motion, or by reflection, interferences and abnormal power losses would be avoided, and the muffling problem itself might be simplified. The scheme selected was rather similar to the muffler design shown in figure 3, page 47, of Report No. 10. The exhaust of each cylinder was to enter, tangentially, the annular space between two concentric cylinders. In this space the exhaust gas, entering with high velocity and pressure, could spin around, dissipating its energy both by friction and by progressive leakage through numerous small holes in the inner cylinders. The inner cylinder, continued outward from the manifold, was to become the exhaust pipe. A design for a manifold-muffler of this type is shown in figure 13. The tangential entrance effects the trapping of the exhaust pulse, preventing its direct or indirect return to any cylinder. This is shown more in detail in figure 14.

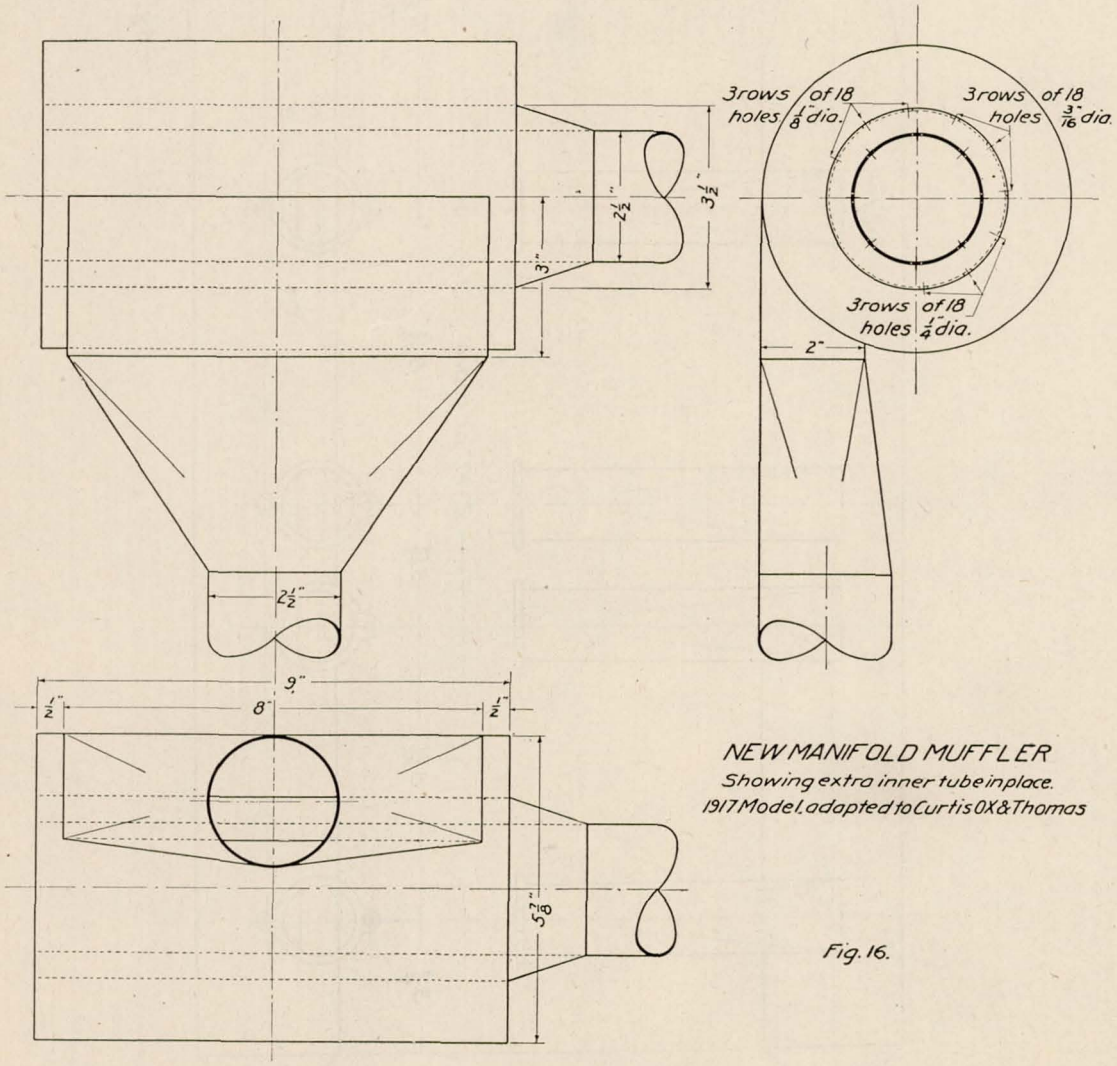
While a device of this character (figure 13) might be successful in normal operation of an automobile engine, it was discarded as unsuited for airplane engine service. First, the internal construction would burn out owing to the great heat of the exhaust gases in airplane service, and secondly, the radiant heat from the large surface of the manifold would prohibit the installation. The first objection may be met, and the second minimized, by the more compact construction suggested in figure 15, which could well be built with a smaller external diameter than the other design.

The remainder of the experimental work consisted of trials of various commercial mufflers and of experimental mufflers designed and built by the authors of this report. The experimental apparatus remained, in general, unchanged. The dynamometer, the tachometer, and the arrangements for reading back pressures remained the same and were used as before. Power losses due to the application of mufflers were found as described previously in the determination of power losses due to applied back pressures. When the emphasis was upon the determination of muffling ability, and the comparison of various mufflers with each other as silencers, the determination of power loss was inferred from the back pressure reading and general engine speed. This method is more accurate than the direct determination of power loss from speed drops, because the power losses from the mufflers finally selected were small. The drop of speed was too small to read satisfactorily while the back pressure was still a readily measurable quantity.

Usually, when working with mufflers, the Curtiss engine was set to run at its recommended speed of 1,200 to 1,250 r. p. m., developing about 70 horsepower. A scale of throttle settings had been made so that this, and other settings, could be duplicated. Generally one muffler was used for the entire engine, taking the exhaust from all eight cylinders. The setup shown in figure 1 was then modified by putting the quick-opening valve on the side outlet of the tee on

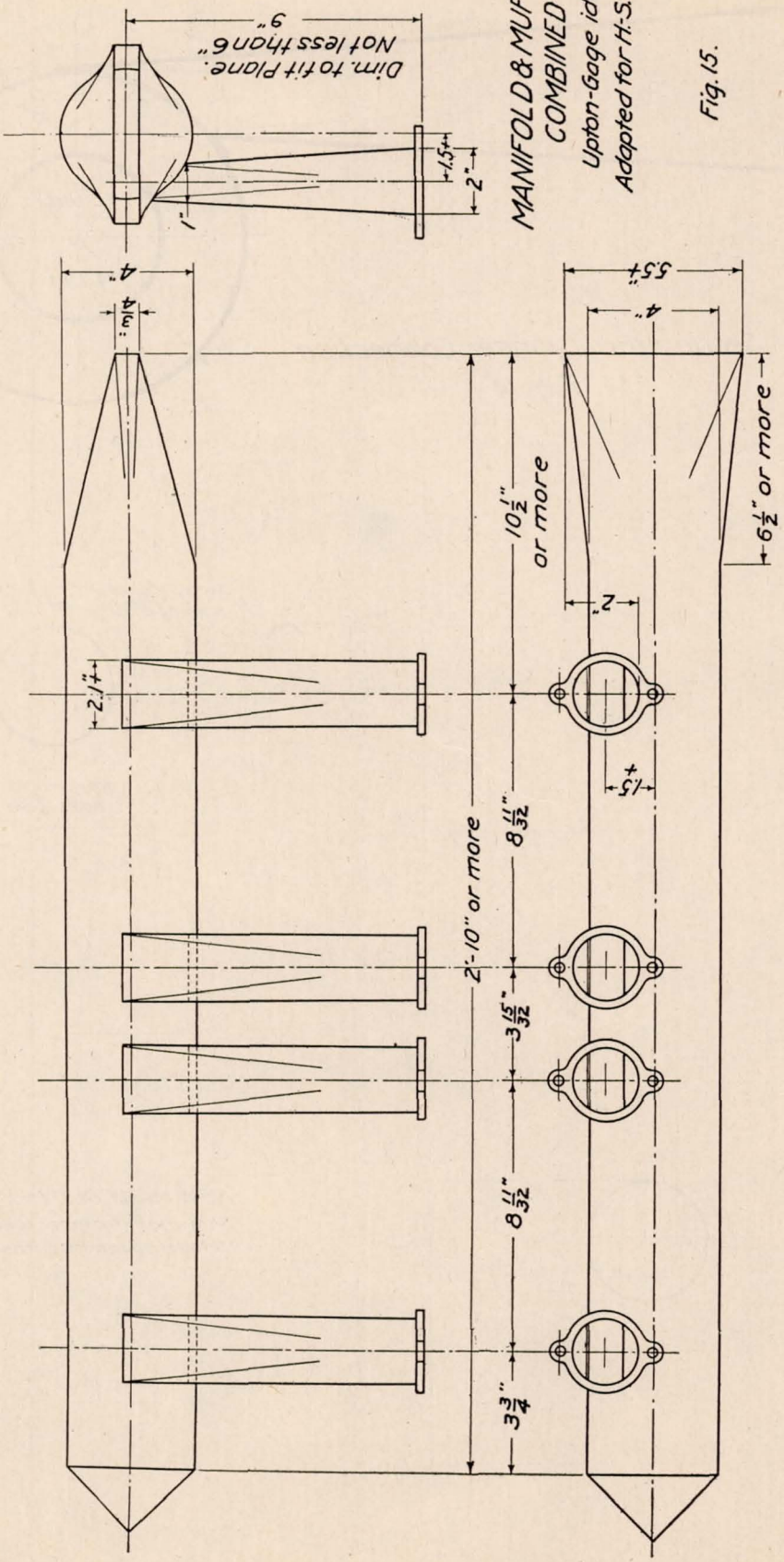


Section thru Cylinder Connection
Fig. 14.



NEW MANIFOLD MUFFLER
Showing extra inner tube in place.
1917 Model, adapted to Curtis OX & Thomas

Fig. 16.


MANIFOLD & MUFFLER COMBINED
Upton-Gage idea.
Adopted for H.S. Eng.
Fig. 15.
Dim. to fit plane. Not less than 6" 9"
1.5"
2"
1"
4"
4 1/4"
5.5"
4"
2"
1.5"
2 1/4"
10 1/2" or more
6 1/2" or more
2'-10" or more
8 11/32"
3 15/32"
8 11/32"
3 3/4"

the end of the cross manifold, allowing the installation of the muffler under test, without a valve, in the direct line of the exhaust flow. The back pressure due to the muffler could then be determined, by taking alternate readings as before, with the quick-opening valve open and shut. The data of Tables III, VI, and part of VII came from this arrangement.

In a few tests, concerning particularly the capacity of mufflers, the cross manifold was removed. A muffler could then be placed directly on the end of the stock exhaust manifold for one block of four cylinders. Generally a muffler was placed on each of the two manifolds. The mufflers then had to be applied and removed by hand in order to determine the back pressure due to the muffler. This procedure was used for getting the data of Table IV, using the G. P. F. 12-inch and 28-inch mufflers, and part of Table VII.

Estimates were always made of the silencing qualities of the muffler being tested. In the end the devices selected as most promising were put through comparative tests, where rapid substitutions were made by hand. For this work it seemed desirable to make an open-air estimation of the noise of the exhaust and the degree of silencing with the various mufflers. To get the exhaust outdoors and pointed in the right direction the tee and valves on the end of the cross manifold were removed. At the end of the cross manifold direct connection was made to a 2-inch piping system consisting of a 6-foot length of pipe, a 45° ell, and a second 6-foot length of pipe. This piping did not muffle the exhaust to any noticeable degree. The back pressure due to the piping, at normal engine speed, was about 1 inch of mercury. This measurement, in itself, may be of considerable interest in the problem of the disposal of engine exhaust on airplanes. The data of Tables VIII and IX were taken with the mufflers placed outdoors in this manner.

Many devices and ideas for silencing were considered, and quite a few were tried out. All devices with which tests were made, and which were found worthy, as well as a few which were rejected, are included in the descriptive matter which follows. Of the rejected schemes, only those are described which are based upon some peculiarly attractive idea, or which are akin to common practice. The experimenters (the authors of this report) applied quite peculiar descriptive nomenclature to some of these devices. For the sake of brevity, some system of naming is necessary, so those designations will be perpetuated, and the derivation of the appellation briefly indicated.

G. P. F.—These mufflers are shown in figure 2 and described on page 43 of Report No. 10. Four of these were used, two each of the two sizes. All were 5 inches diameter, two were 12 inches long, the other two were 28 inches long. They were made by Geuder, Paeschke & Frey Co. These are regular stock mufflers.

Maxim.—A Maxim silencer for Fords was purchased of a local garage. The entrance to this muffler was only 1.5 inches internal diameter. The tail pipe was 12 inches long, tapering from 1.5 inches diameter at the muffler to 1 inch diameter at the outlet. It was hardly fair to use this on a 70 horsepower engine; but the data is of great interest.

Manifold mufflers.—The name comes from the original idea of putting several of these devices in line, end to end, one for each cylinder, the combination to replace the exhaust manifold. However, this manifolding scheme was never thoroughly tried out; the one unit of the device was used as a muffler, with conventional installation at the end of the manifold. As originally constructed the inner cylinder did not touch the end plate, so that the exhaust could escape around the end as well as through the holes of the inner cylinder. The end path could be blocked by a piece of asbestos board fastened to the end plate. This first manifold muffler was of the same general design as shown in figure 16 and figure 17, but with the outer cylinder 6 inches long instead of 9 inches, and containing only the 3½ inch perforated inner tube.

The "Long Manifold Muffler" was made up of two outer sections of the first manifold muffler, making an outer cylinder 12 inches long. The inner tube was not perforated and extended the full length of the muffler, its serrated end touching the far end plate. The exhaust entered the outer cylinder near one end through the regular tangential entrance of this type of muffler. The entrance of the second unit was blocked. The annular space was both spin and

expansion chamber for the exhaust gases, which escaped into the inner tube only through its serrated end, at the opposite end of the muffler from the gas entrance and exit.

Later a "New Manifold Muffler" was built similar to the sections which were first made, but 3 inches longer, and with provision for slipping an extra perforated inner tube of 2½ inches diameter inside of the regular 3½-inch inner cylinder. This last design of the manifold muffler is shown in figure 16, with the extra inner tube in place, and in figure 17 assembled and disassembled. The manifold mufflers are developments of the muffler shown in figure 3, page 47, of Report No. 10.

Wire mesh type.—Several of this type were built and tried out. The general scheme is shown in figure 4, page 48, of the Report No. 10. The idea is to gradually increase the resistance, and to break up the energy, of the exhaust by means of sections filled with fine wire mesh. The finest mesh was used at the outlet, and the mesh increasing in size toward the engine.

Spiral guide vane.—This scheme consisted of an expansion chamber, with spirals in the annular outlet passage, instead of the wire mesh. The spirals formed, in effect, a long nozzle. Various forms of spiral were tried: of constant pitch, or area of passage; with area of passage growing smaller toward the outlet, forming a sort of converging nozzle, and with the area of passage increasing toward the discharge end. The general design of these is based on that of the Maxim silencer, but there is not the repeated reversal of flow in the spirals.

Whirl chamber mufflers.—So called from their general construction. Figures 17, 18, 19, and 20 show the form of these mufflers. The exhaust pipe is flattened from a circular cross section at the engine to a rectangle at the muffler, giving a contracted nozzle effect. This rectangular section is fastened tangentially to the circumference of a ring of considerably larger diameter. One cover plate for one side of the ring is a plate dished to give stiffness. The other cover is the outlet for the gas, and consists of a truncated cone. The exhaust gases enter the ring tangentially, swirling around and around inside the ring. As they lose velocity they gradually escape through the opening between the dished cover plate and the end of the truncated cone. Four of these mufflers were made, one each with rings 4 inches and 12 inches in diameter, two with 7-inch diameter rings. The 4-inch and 12-inch diameter were made with the idea of having one of them too small and the other too large. The exhaust pipe entering the muffler was contracted from a 2-inch diameter to a rectangle 1-inch wide, except that one 7-inch ring had a nozzle ½ inch wide. The sides of the rectangle had the same total perimeter as the circumference of a 2-inch circle. This is a constructional requirement. The width, or depth, of the cylindrical ring was limited to the length of the rectangular discharge nozzle, plus clearance necessary in manufacture. This makes the rings 4 inches deep with the 1-inch nozzles, and 4½ inches with the ½-inch nozzle used on one of the 7-inch whirl chambers. The cover plates were dished about ¼ inch, this being the maximum obtainable with the local tinsmith. The design called for ½ inch. These plates could be applied with the convex surface in or out as indicated in figure 19. The area of the open end of the truncated cone was the same as that of the exhaust pipe, that is, 2 inches diameter. The space between the end of the truncated cone and the cover plate was varied from time to time by the various arrangements, some of which are indicated in figure 19. Shallow cones were available as well as the deep ones. With deep cone, and cover plate dished inward, the clearance through which the exhaust had to escape was about ¼ inch. With cover plate dished outward the clearance became ¾ inch. With shallow cone the clearance was 1½ inches.

The 7-inch whirl chamber muffler was also tried out with a double cone assembly, one cone pointed inward and one outward. (Diagram of arrangement in Table VII.) This assembly was also tried with a "diffuser" plate between the two cones. One diffuser was a plate with about 100 scattered $\frac{3}{16}$-inch holes punched through it. Another diffuser tried with both 7-inch and 12-inch whirl chambers had no holes, or very small ones, in the 120° sector first passed by the entering gas, the next 120° with larger holes, and still larger holes in last 120°.

The *Duplex whirl chamber muffler* consisted of the two 7-inch rings bolted end to end, using one of the tangential nozzles as entrance, and the other as discharge passage. The arrangement required the reversal of internal whirling before the gas could get out. Generally one or the

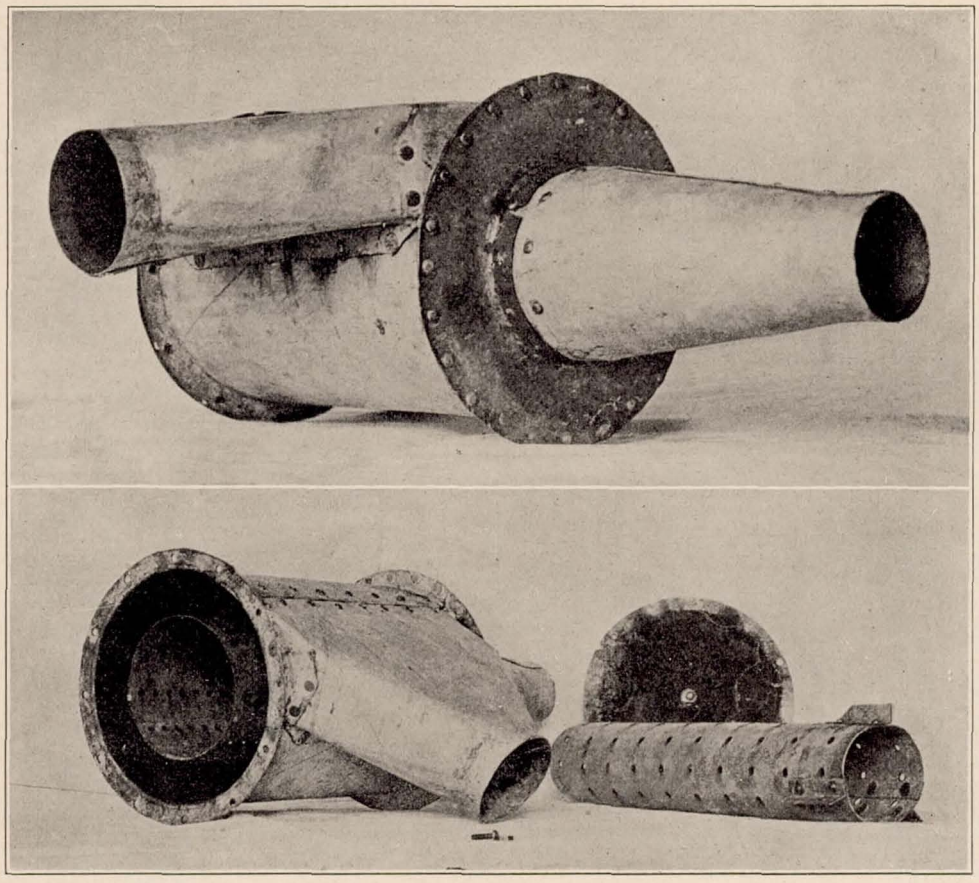


FIG. 17.

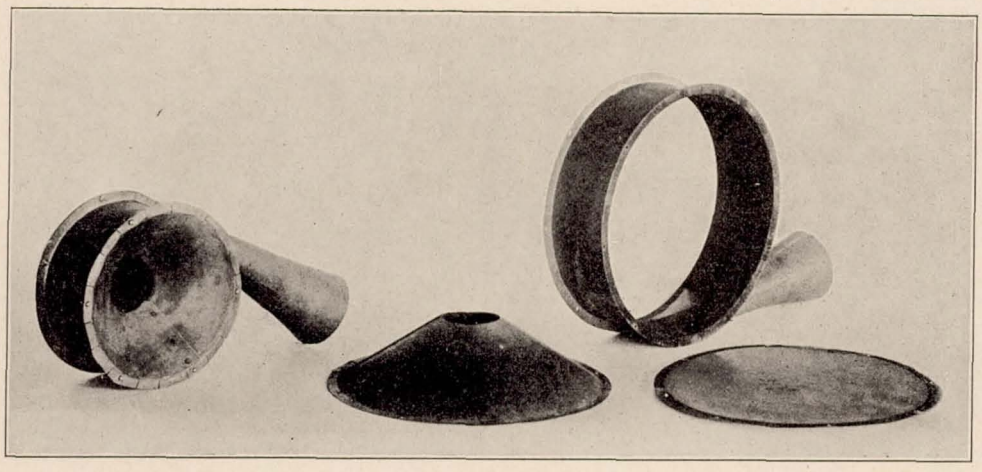
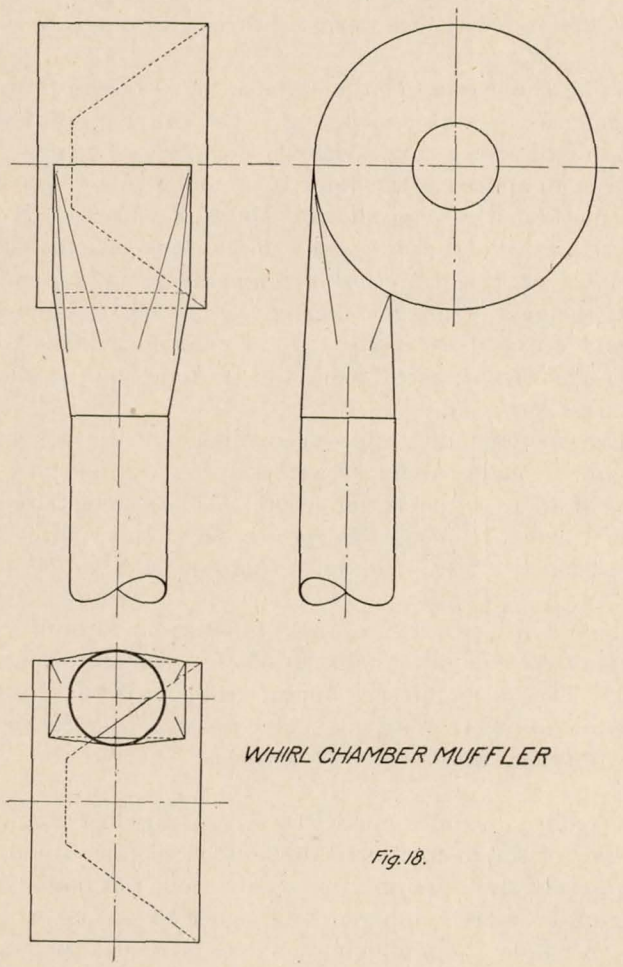


FIG. 20.

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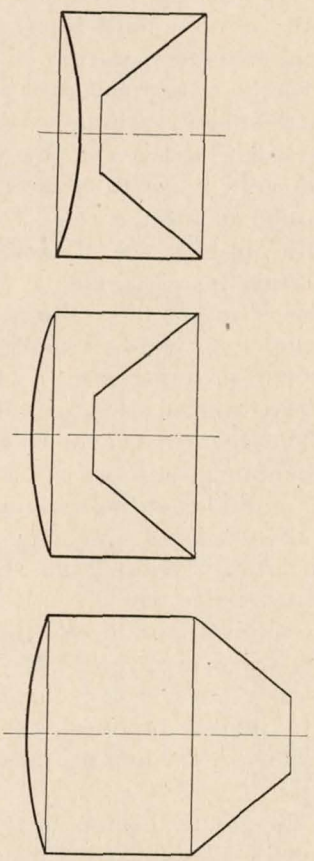
other of the diffuser plates was placed between the two rings. The 1-inch nozzle was used as entrance in most cases.

Venturi.—A 2-inch pipe Venturi with ¾ inch throat was tried, upon the idea of an expanding nozzle to secure an adiabatic drop of pressure and temperature of the gas, also, to increase the velocity of the gas above the velocity of sound, so as to prevent any sound waves issuing from inside the manifold. The Venturi was used alone, and in combination with the 7-inch whirl chamber muffler, the Venturi then acting as a discharge pipe.



WHIRL CHAMBER MUFFLER

Fig. 18.



VARIOUS ASSEMBLIES OF WHIRL CHAMBER MUFFLERS

Fig. 19

The problem of silencing the exhaust noise from an internal combustion engine is fairly comparable with the problem of silencing a high velocity rifle, or better, a machine gun. At the instant that an exhaust valve begins to open, the gases seeking to escape from the cylinder have a pressure in the neighborhood of 40 pounds per square inch gauge and temperatures of the order of 1,000° F. Where the endeavor is to get maximum power from the engine, these values are understated. If adiabatic expansion is assumed at the time of release, the initial velocity of the discharging gas is independent of the pressure into which the gas is escaping, because the "critical pressure" is greater than the pressure in the manifold or atmosphere. The initial velocity will be the velocity of sound at the "critical" pressure and existing temperature of the gas at this pressure. This velocity of the exhaust gas is of the order of 1,500 to 2,000 feet per second—considerably higher than the velocity of sound through the air. The first portion of the escaping exhaust is practically a slug of gas coming out like a projectile from a gun, with a velocity greater than that of sound in air.

It is well recognized that the report of a high-velocity rifle consists of two sounds. One sound wave, the "report," comes from the muzzle of the gun arising from the slap of bullet and

exhaust gas upon the air adjacent to the muzzle. The other sound, of cracking, ripping quality, comes from the tearing of the air by a projectile moving with a velocity in excess of the velocity of sound. If the bullet is traveling toward the observer, this second sound is heard first. The slugs of exhaust gas from the open exhausts of an airplane motor are soon dissipated, and do not travel far as projectiles. While they last, however, there is little doubt that they contribute to the quality and amount of exhaust noise from the engine.

If the velocity of the slugs of exhaust gas at the time when they enter the air can be reduced below the velocity of sound in air, the quality of the exhaust sound will be much duller and the quantity of noise much less. The most effective way of lowering the velocity of sound in a gas is to lower its temperature.

There are two means of accomplishing the cooling of the exhaust gases before they reach the atmosphere. One is by direct cooling, as by water jacketing. The other is by designing the exhaust passages on the idea of the nozzles of a single velocity stage steam turbine, so as to reduce the velocity of the exhaust gases to approach the velocity of sound in air, by efficient expansion in the nozzles. This latter method was suggested by Mr. F. C. Mock. (S. A. E. Bulletin, p. 270, Vol. V, No. 3, Dec., 1913.) It was found that such design of exhaust ports apparently increased engine power. However, the reduction of temperature by expanding in nozzles is limited, if no work is done by the gas. Only the edge of the crack of the noise from the slug of gas can be removed by means of expansion alone. If the exhaust is made to drive a turbine, then more heat energy will be abstracted, useful work will be done, and at the same time the exhaust velocities will be made uniform and small.

The frequency of the exhaust from a multicylinder, high-speed engine generally is a source of a humming sound, if in any way the air is made to vibrate with the engine frequency. The lowest audible note to the human ear is of about 40 beats per second. The exhaust frequency of a 12-cylinder 4-cycle engine running 1,500 r. p. m. is 150 per second. This will be a low-toned hum. To this hum an airplane propeller also contributes harmonics which will blend with the engine hum.

Complete muffling, so that the engine will give neither crack, whistle, nor hum of exhaust noises would involve the smoothing out of the flow of exhaust gases into the atmosphere to a uniform velocity below that of sound. This is manifestly impracticable. With a pulsating flow it might be practicable to keep the maximum velocity of exhaust gas entering the air below the velocity of sound in the air. The humming noise will then be heard, without the crack or whistle.

The greater portion of the exhaust from a cylinder must pass out in this first slug of high velocity discharge, as the average velocity of the piston on the exhaust stroke is only about 25 feet per second. This shows that the actual time required for discharging the major portion of the exhaust of any one cylinder is quite short compared to the period during which the exhaust valve of this cylinder is open. A whole group of cylinders may be discharging into one exhaust manifold without interferences, provided the manifold is so designed that each slug of exhaust can freely escape down the manifold without check or reflection. If too many cylinders exhaust into one manifold, there will be overlap of the scavenging periods, during which two or more of the various exhaust valves may be open at the same time. This overlap of the scavenging periods is a minor matter compared to what happens when a slug of exhaust enters some cylinder through an open exhaust valve directly or by reflection.

An exhaust manifold may reduce the crack of the exhaust by slowing down the initial velocity of the slugs of gas, and by a limited amount of cooling. The direction in which the exhaust is pointed is a considerable factor in the noise heard by observers, the intensity of sound being much greater in the direction of projection. Long exhaust pipes may somewhat increase the muffling effect of a manifold, by added friction and added cooling. However, the notation on Table VII, based upon the estimates of several observers, would indicate that muffling effect of manifold and long smooth exhaust pipe was very slight. Bends, and also rough interior surfaces, will increase the muffling effect and also the power loss.

Any long pipe may act as does an organ pipe, having a natural period of vibration in sound waves. This period may happen to coincide with the frequency of the exhaust in such a way

that exhaust gas will be forced back into some cylinder just before the closing of its exhaust valve, entailing an abnormal power loss at a critical speed. Such an effect was noted in the experimental work, and was referred to in the discussion of Table II.

As previously stated, the silencing problem would be solved if it were feasible to reduce the velocity of exhaust gases escaping into the air to a uniform velocity, less than the velocity of sound. Practically, it is possible only to spread out the peak of the discharge, or the "slug" of exhaust pulse, so that its velocity is reduced toward that of sound. Every slug of exhaust, not only while in the exhaust system but in the period of issuing from the system, is a potential source and exciter of sound waves. The internal vibrations of the system as excited by each slug, combine their sound with that of the impact of the slug upon the air, and change the quality of the sound as a whole. Great irregularities of internal form of the exhaust system may break up the internal sound waves. The sound-producing qualities of the exhaust slug are relatively much greater than the sound waves internal in the exhaust system.

A very obvious device for dissipating the excessive velocity of initial flow of each exhaust is an expansion chamber. The gas velocity entering the chamber is highly irregular; it is assumed that the discharge velocity is much more nearly uniform; and the slapping of the external air by successive exhaust slugs is stopped. This is nearly true if the chamber is capacious enough. The slapping action takes place as theexhaust enters the expansion chamber, and sound waves from this point radiate outward, some of them escaping through the tail pipe. To complete this device as a muffler, the exit of sound waves would have to be prevented, it being assumed that the capacity of the chamber is sufficient to prevent the slug passing through as such.

If through the exhaust line there is placed a long series of baffles, each baffle will drag back a portion of a passing exhaust slug, delaying this portion with reference to the remainder, and thus changing the flow from intermittent to nearly uniform. Muffling might then be secured by a sufficient amount of baffling alone. The cost in back pressure and power loss would be prohibitive, to say nothing of the weight of material necessary for the baffles and general structure. When baffling structures are used, the highly heated exhaust gases burn out the internal structure, and carbon deposits and oxide scale choke the baffles. This burning away of internal parts is a very serious objection to the use of baffles in mufflers for airplane motors.

A combination of expansion chamber and baffles can be made into a very satisfactory muffler. The smoothing of the pulsations of the exhaust flow is done mainly by the expansion chamber, and with much less power loss than if it were done by baffles. The baffles permit the expansion chamber to be made of moderate dimensions, by helping the smoothing out of the flow. Also, if properly designed, they will nearly prevent the escape of sound waves from the expansion chamber by reflection (backward) and dispersion (scattering and interference) of the sound waves coming from the initial slap of the slug.

In order to get the effect of a large expansion chamber without great weight and size, the manifold muffler type ("whirl chamber") construction was proposed. The exhaust is brought tangentially into an annular space between two concentric cylinders. The slugs of exhaust gas may continue to travel around in this space, but they can not escape from this cylinder until their velocity is sufficiently reduced to reverse or change direction in some way. If, for example, the gas slug whirls around the chamber 20 times (it was observed to travel around more times than this upon a single cylinder slow-speed engine) it has had, in effect, the use of an expansion chamber of a volume 20 times the volume of the annulus. As the gas spins, losing velocity, a continued series of small portions escape, at right angles, into the inner cylinder or discharge passage. The gas can more readily turn at right angles than reverse itself, so that there is little chance for a return pulse to the cylinder. In spinning around and escaping inwards, a subdivision of the exhaust pulse is made such that the successive small portions enter the atmosphere over a comparatively long period of time, making the velocity of the exhaust gas entering the air fairly uniform instead of highly intermittent. It is also probable that the initial slap of exhaust entering the whirl chamber of the mufflers is less than if they abruptly entered a large expansion chamber, because there is relatively a much smaller change of size of passage. As contrasted with the use of baffles to smooth out the exhaust pulsations, the desired end is

accomplished in these "whirl chamber" designs (and "manifold mufflers") with relatively less power loss through back pressure.

In the typical "whirl chamber mufflers" all metal parts had one side exposed to the air in order to have considerable cooling effect upon the exhaust, and also to avoid the danger of the burning away of the metal. (The success of this cooling is illustrated upon one of the mufflers tested, which still has upon it a paper label only slightly charred.) In so far as any cooling of exhaust is secured, the muffling is thereby aided.

A sufficient cooling of the gas will, in itself, silence the exhaust. Such cooling is only possible in marine practice, where water is sprayed into the exhaust line, and is found effective. It may be desirable to place fins for air cooling upon the exhaust manifolds, pipes, and mufflers of airplanes. A radiator used to cool the exhaust gases for the purposes of silencing may sound like a humorous suggestion, and yet it may be practical on heavy duty planes.

Before a muffler can be applied to an engine there must be a manifold of some kind to take the exhaust gases from the engine to the muffler. This manifold is itself a source of power loss, both through friction of flow, and through the possible interferences already mentioned, particularly the back flow of exhausts. In the early days of internal combustion engines, manifolds were first made by bringing the pipes from the individual cylinders squarely into a collecting pipe. The right angled turns of this design caused high back pressure and promoted interferences. To decrease the back pressures (and interferences) the manifolds are now made with sweeping curves on the discharge pipes of each cylinder, making each individual pipe have an easy entrance, in the direction of flow, into the common pipe. It is suggested that a more compact design could be made by analogy with the "whirl chamber mufflers." The individual exhaust pipes might be brought straight out from the cylinders, but with their center lines so far above or below the center line of the common pipe that the exhausts would make tangential entrance to the common pipe. This idea is shown in the designs of figures 13, 14, and 15. The change of direction of flow from the individual pipes to the common pipe can probably be made with back pressures no larger than from the sweeping bends of the conventional construction, and with the advantage of compactness. The smallness of back pressures may be inferred from the data at the bottom of Table VI on the resistances of rings with nozzles only.

Throughout all the design of manifolds and mufflers there is one item that must be kept continually in mind. The sharp pulse of each exhaust is practically a mechanical slap or blow upon all of the inside surfaces of the metal parts. If these metal parts are made of thin material, as they must be to save weight, it is necessary to so form them that they are inherently stiff, incapable of buckling or drumming. Otherwise they will become transmitters for the exhaust sound to the adjacent air, with additional noises from the reverberation of the metal itself. Flat surfaces are to be avoided, and doubly or singly curved surfaces chosen.

The preceding paragraphs have outlined the theory of muffling and associated problems as it developed to the authors during and after their experimental work.

Early in the work there arose the question of how the capacity rating of a muffler should be made. The data of Table IV precipitated this question. The two different sized mufflers compared were presumably alike in internal design save that the longer ones contained a greater number of the baffling elements in series. The G. P. F. design is given in figure 2 of Report No. 10. According to the makers the horsepower capacity to be handled by the 28-inch mufflers is four times that of the 12 inch. They recommended the 12-inch mufflers for engines up to 553 cubic inches displacement, and the 28-inch mufflers for engines up to 138 cubic inches. Yet it was found that on the Curtiss engine, with one muffler handling 4 cylinders, of 251 cubic inches displacement, the 12-inch mufflers gave 2 inches of mercury back pressure, against 4 inches from the 28-inch mufflers, and if there was any choice as to silencing ability, the smaller mufflers were the better. It was also found that the 12-inch G. P. F. muffler failed to silence a $3\frac{11}{16}$ by 4 inch Chevrolet automobile motor of about 170 cubic inches displacement. This same 12-inch G. P. F. muffler gave the same back pressure and better silencing effect when handling all 8 cylinders of the Curtiss engine (Table VIII) 502 cubic inches displacement, that it did when handling only 4 cylinders of the same engine.

In Table VII the data shows that one of the "manifold mufflers" had this same peculiarity of improving its silencing, and of not increasing its back pressure when the number of cylinders handled was changed from 4 to 8. At the same time some "whirl chamber mufflers" increased their back pressure in the ratio of 1 to 1½ or 1 to 2 when changed from handling 4 to handling 8 cylinders. If the back pressure of a muffler followed the usual laws controlling the increase of pressure with quantity passing, the doubling of number of cylinders exhausting into a muffler should have multiplied the back pressures by 4. The explanation is in part in the design of the mufflers themselves, and in part due to the peculiarly intermittent flow of the exhaust gases.

The silencing by the muffler comes in its operation upon the "slugs" of the exhaust gas, the size and character of which is fixed by the individual cylinders. In so far as the frequency of impulse (due either to multiplication of the number of cylinders or to the increase of speed) is concerned, it appears that the more frequent the impulse, the easier it is to silence the exhaust noise. The power loss, or back pressure, seems to depend upon the form and size of the individual impulses. Perhaps if the number of cylinders should exceed the present limit (12) there might be sufficient overlap of instantaneous impulses to require a larger muffler. The bulk of the exhaust comes at the first opening of the valve, so these pulses are not liable to be superposed to any appreciable extent. The characteristics of the individual exhaust pulses are controlled by volume of cylinder, valve timing, throttle position, ignition timing, and mixture ratio, all of these affecting the amount of gas and its pressure at the time of opening the exhaust valve. The speed of an airplane engine is tied with the throttle position because of propeller characteristics, while an automobile engine throttle and speed are independent.

As a matter of fact, it appears that the smaller the mufflers, up to some limit, the better the silencing. Also the larger the muffler, the less the back pressure, geometric similarity being assumed. (The 28-inch G. P. F. muffler is not similar to the 12 inch.) The effect of change in back pressure is slight. So that the tentative conclusion is reached that, with the muffler design geometrically fixed, and if the size only is changed, then the smaller the muffler the better the silencing and all around action, until the power loss exceeds the tolerated value.

It may be remarked that mufflers taking all 8 cylinders of the Curtiss engine receive about the same frequency and magnitude of impulse as if used on one side, 4 cylinders, of back geared motors such as the Thomas or Sturtevant.

The effect of size of muffler was noted when using the same mufflers on different engines. The greater the bark of the exhaust, the better was the relative suppression by the same muffler. The mufflers were more effective in suppressing the bark of the single cylinder farm engine (5½ by 10 inch Ingeco) than on the Curtiss (4 by 5 inches).

The suggestion from the facts mentioned above is that the capacity rating of a muffler probably should not be based upon the total displacement of the engine, so much as on the displacement per cylinder.

In reading the discussion which follows concerning the various schemes for silencing the exhaust which were considered in this work, it should be kept in mind that the experimenters had formulated certain requirements and limitations for mufflers in airplane service. The manifolding and mufflers should not be a source of fire risk from radiant heat. Muffler explosions should be made harmless, either through sufficient strength, or provision of a breaking piece. Weight of manifolds and mufflers must not be excessive. Any parts so disposed as to cause head resistance must be made as small as possible and of "stream line" form. The power lost due to back pressure must also be very small. It is desirable, but not essential, that the muffler be durable, especially with regard to burning out the interior parts. The amount of silencing required is not great, compared to the usual ideas of muffling devices as exemplified on automobiles. The reason for not requiring so effective silencing is that there are many other noises coming from a plane moving through the air. Such noises are the hiss or whistle of the wires, the beat or drum of the propeller, and the valve and gear noises from the engine. It has been assumed in this report that what the experimenters and assistants called a 50 per cent total silencing of the exhaust noise would be sufficient and satisfactory for airplanes. If there is more silencing than this, a muffler cut-out may be needed by the pilot to judge the

engine performance. However, it was found that 75 per cent silencing was easily obtained, so this was soon adopted as a standard.

A common device on planes is a long exhaust pointed upward. This is not a muffler, but it is somewhat effective in directing the sound away from the ground. Long pipes running back along the fuselage take the exhaust gas and some of the noise away from the occupants of the plane. If pipes of smooth interior are used, the power loss due to back pressure is relatively small. In Table VIII it is noted that 12 feet of 2-inch pipe with one 45° elbow caused a back pressure of 1 inch of mercury on a Curtiss (8-cylinder OX) engine, resulting in a power loss of about seven-tenths of 1 per cent. It is regretted that data on the back pressure due to flexible metallic exhaust hose was lost, but the notation made was that 4 feet of the 2-inch flexible hose gave more back pressure than the 12 feet of standard 2-inch wrought-iron pipe including one 45° elbow.

The first muffler tried out in this series of tests was a wire mesh muffler shown in figure 4 of Report No. 10. The muffler type is that of expansion chamber plus baffles, relying largely upon the baffles for noise suppression. The power loss was slight and the muffling estimated about 50 per cent. The weight is 15 pounds, which is comparatively great. The flat metal sides probably drummed, reducing the muffling ability. It was anticipated that the wire gauze would burn out and choke the passages with scale under continuous operation. Even in short operation the wire gauze began to pack although it did not burn. These prospective troubles, together with the weight, caused the discarding of this type.

The variable pitch spiral muffler mentioned in Table V, was, as constructed, cumbersome. Its silencing was estimated at 50 per cent plus. The construction embodied a cylindrical expansion chamber plus a baffle placed in a concentric annular space. The baffle was made of a single strip, helically wound around the chamber, making, in effect, a long unobstructed path. This device is of the same type as a number of commercial mufflers which have already been more highly developed. It is subject to the disadvantages of weight, size, and burning out.

A Venturi with throat 0.75 inch diameter and of 2-inch entrance and exit was tried on the end of the 2-inch exhaust pipe. The throat size was selected to give a gas velocity greater than the velocity of sound, in order to prevent the transmission of sound from the engine through the exhaust pipe. The success was undoubted, as there was no crack. But the velocity of the gas in the throat set up an unearthly noise all its own. The expanding portion of the Venturi, instead of serving as a diverging nozzle, acted as a megaphone. Then the Venturi was tried with the exhaust first passing through the 7-inch "whirl chamber" muffler, with somewhat similar results. The Venturi was also rejected.

The Ford Maxim muffler was found to be a very effective silencer when used upon the Curtiss engine, as well as when used on a Ford automobile. On the Curtiss engine, handling all 8 cylinders, the power loss was rather high compared with some other devices. Considering the fact that the muffler was built for a small engine (the tail pipe was 1 inch diameter), this is hardly to be wondered at. The weight of 12 pounds was prohibitive.

Throughout the experimental work the G. P. F. 12-inch muffler was used as an arbitrary standard of muffling qualities. It appears repeatedly in the tables on account of this. While estimates of noise suppression were attempted in absolute values, the final decision always rested upon relative performance. The "Remarks" of Tables VIII and IX will illustrate this. The G. P. F. 12-inch muffler construction, as shown in figure 2 of Report No. 10, is novel. The baffles, in the form of nozzles, occupy the expansion chamber. The parts are few and simple. Surfaces are doubly curved, making for inherent stiffness. The peculiar fact was noted that this muffler worked equally well with either end as entrance, both as to back pressure and silencing. There is a possibility that the internal parts may act as dispersers of the sound waves by reflection, as well as other ways.

Our attempts to design mufflers, especially adapted to airplane use, have followed two main lines. The "manifold" series of designs use tangential entrance to an annular whirl chamber, the gases gradually escaping to the central part as they spin. The spin chamber gives the effect of the conventional expansion chamber with a much smaller volume. The perforated inner tube replaces the baffles, with less weight and back pressure. The objection

to the construction is that the inner cylinder may burn out. To avoid this objection the "whirl chamber" series was designed. The action is essentially the same as the "manifold" type, but all metal parts are air cooled on one side, and the weight is less. A particular study of the "whirl chamber" type is given in Tables VI and VII. While making the observations on bark suppression, using the Ingeco engine (Table VI), the tests were made with load, at about 100 explosions a minute, and with retarded spark to give a vicious bark. The exhaust was flaming as it issued from the engine, and gave visual demonstration of the spinning action in the whirl chamber, and of the gradual emission of gas from the muffler.

Both "manifold" and "whirl chamber" types have a peculiarity that may be advantageous. The exhaust is turned at right angles between the entrance and discharge of the muffler, and with very little back pressure. Roughly, the back pressure is less than when using an ordinary pipe-fitting elbow. Short tail pipes of diameter equal to the manifolds were tried upon these types of mufflers, and were found not to affect either silencing or back pressure. So these mufflers might be placed at the end of a horizontal manifold, and the muffler tail pipe be carried vertically upward.

The data from the different tables in this report should not be indiscriminately compared. The manifolding conditions were frequently changed. In Tables VIII and IX the manifolding arrangements were the same, apparently, but actually were not constant. The increasing vibration of the engine continually shook loose the packing of the joints of the complicated exhaust line. Leaking of the exhaust from the manifolds became noticeable and evidently serious. Part of the piping was made of flexible metallic hose, from which the asbestos packing departed. These troubles make it improper to compare the data of Tables VIII and IX directly with the other tables, especially in regard to back pressure. However, the small group of tests, marked off by themselves in these tables, are correct for relative internal comparisons. To show how these increasing leaks affected back pressure results, the diagrammatic Table X is given. With the aid of this diagram, applied to the data given in the previous tables, the summing of results as given in Table XI is derived. Power losses are here inferred from the curve established in plot 2.

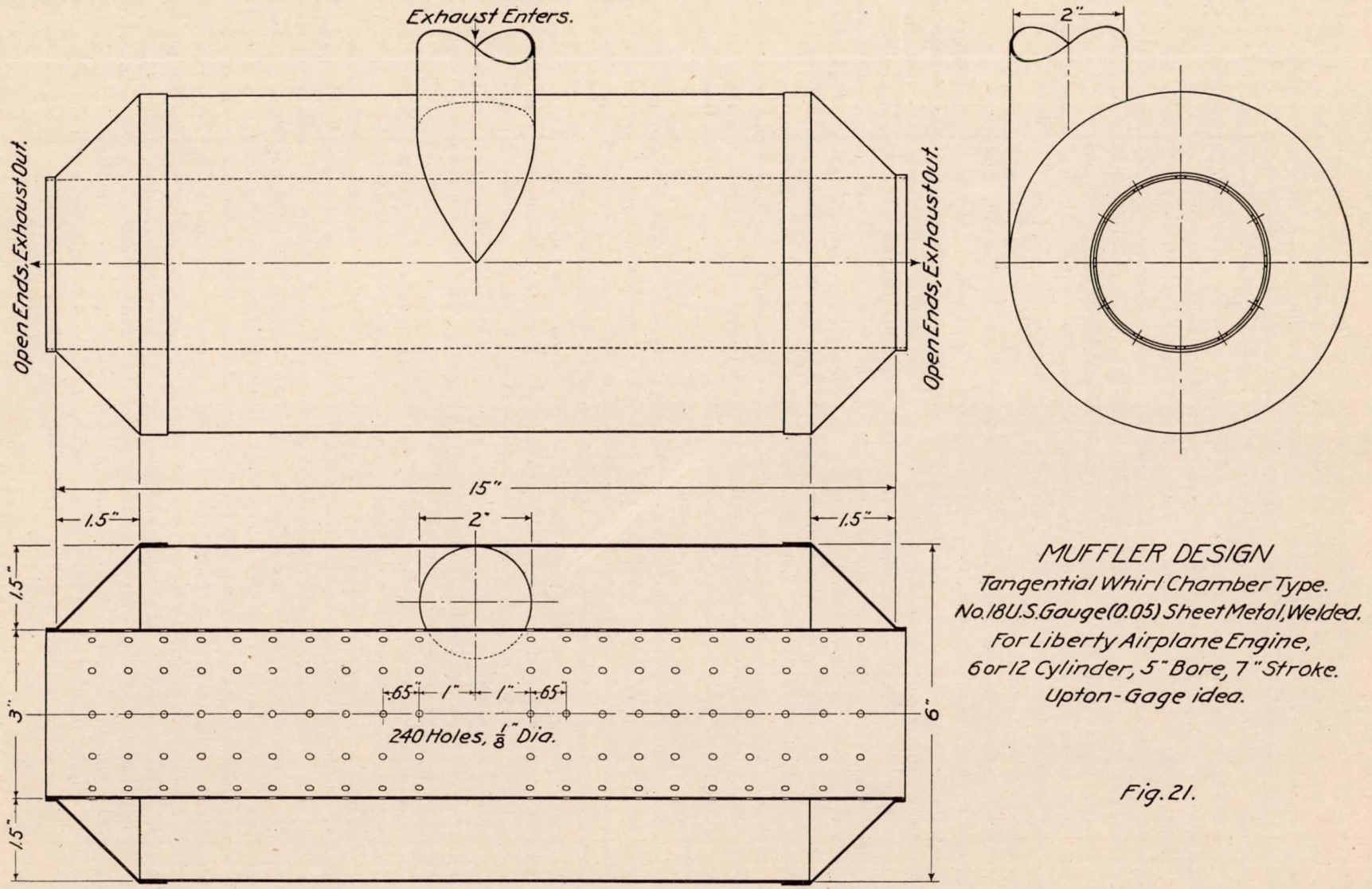
It is evident from this table that the "manifold" type of muffler will give good silencing with power losses less than 1 per cent and with weights comparing very favorably with any commercial muffler. If minimum weights are desired, the "whirl chamber" type looks most promising although its silencing action is not as good as the manifold type.

In the "manifold" muffler type the size, shape, location, and total area of the holes in the inner tube may be varied over a considerable extent. We used a total area of all holes equal about one-half the area of the exhaust pipe with very good results, and deviations did not alter the action of the muffler to any great extent, although many small holes probably gave better muffling without corresponding increase of back pressure. The best construction happened to have no holes opposite the entering gas, 33 holes $\frac{1}{8}$-inch diameter which the gas first passed, 33 holes $\frac{3}{16}$-inch diameter next, and 33 holes $\frac{1}{4}$-inch diameter last, just under the nozzle. We do not lay particular stress upon the size or location, except they shall not be too big.

Taking all the results as shown in plot 10 into consideration, we have recommended, as a tentative design for the Liberty 12-cylinder engine, the design shown in figure 21. A variant of this is given in figure 22. Both designs may possibly be improved by the addition of cooling fins. They are supposed to be placed at the end of an exhaust manifold handling the exhaust from either six or twelve cylinders. The length of the muffler is to be parallel to the fuselage. There is no real attempt to stream line the back end of these mufflers for the stream of escaping exhaust gas is supposed to perform this function. Also any suction at the back end of the mufflers due to lack of stream lining may be worth its cost. In figure 21 is shown a design in which air is supposed to pass through the inner tube to some extent, aiding in cooling.

It is possible that very effective silencing could be obtained if the exhaust manifold were patterned after the design shown in figure 15, in combination with a muffler.

The completion of the solution of the muffling problem can only be accomplished by trials at fitting manifolds, mufflers, and tail pipes to engines installed in airplanes and in use in actual flight.



MUFFLER DESIGN
Tangential Whirl Chamber Type.
No. 18 U.S. Gauge (0.05) Sheet Metal, Welded.
For Liberty Airplane Engine,
6 or 12 Cylinder, 5" Bore, 7" Stroke.
Upton-Gage idea.

Fig. 21.

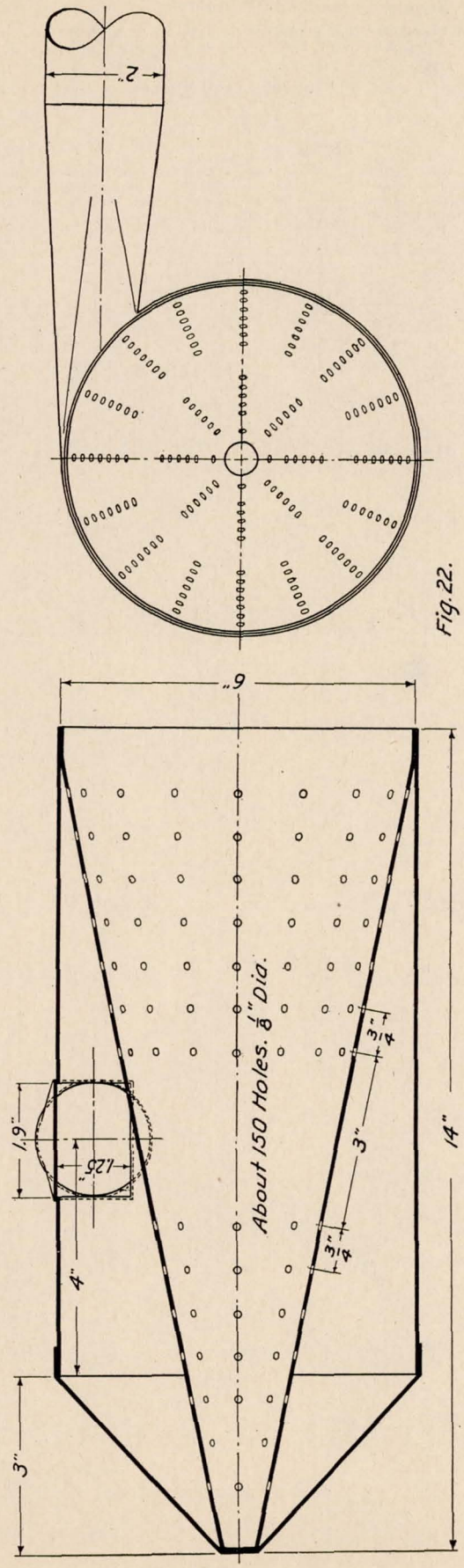


Fig. 22.

TENTATIVE SUGGESTION FOR MUFFLER
No. 18 U.S. Gauge (0.05) Sheet Metal, Welded.
For Airplane Engine, 6 or 12 Cylinder, 5" Bore, 7" Stroke.

TABLE I.—*Runs at constant throttle, varying back pressures.*

Throttle set to run the engine approximately at the power recommended by the maker, 70 B. H. P. at 1,250 r. p. m., with no applied back pressure except that due to the manifolds and piping. Table shows changes by applied back pressure. Data of Aug. 24 and 29.

Observations.				Results. (Based on average of observations.)											
Position of end outlet valve.	Back pressure (inches of mercury).		Tachometer reading (r.p.m.)	Position of end outlet valve.	Average tachometer (r.p.m.)	Average back pressure (in. mercury).	Applied back pressure (in. mercury).	Speed change, not corrected (r.p.m.)	Percent speed change (max. r.p.m. =100 per ct.)	Percent power loss.	True speed (r.p.m.)	Brake horsepower.	Brake M. E. P. (pounds per square inch).	Loss of brake M. E. P. due to applied back pressure.	
	South side.	North side.													
Shut	0.75	0.75	1,120												Aug. 24, 1916
Open	.50	.45	1,120	Open	1,120	0.47	0.34	0	0	0	1,223	64.7	83.5	0	
Shut	.85	.90	1,120	Shut	1,120	.81					1,223	64.7	83.5		
Shut	1.6	1.7	1,130												
Open	.5	.5	1,135	Open	1,135	.5	1.2	5	.44	1.3	1,239	67.3	85.7	0.8	
Shut	1.8	1.7	1,125+	Shut	1,130	1.7					1,233	66.3	84.9		
Open	.5	.5	1,130+												
Shut	3.2	3.1	1,125												
Open	.5	.5	1,135+	Open	1,137	.5	2.75	11	.968	2.9	1,241	67.6	85.9	1.6	
Shut	3.4	3.3	1,125+	Shut	1,126	3.25					1,229	65.7	84.3		
Open	.5	.5	1,135+												
Shut	5.4	5.1	1,085+												
Open	.5	.4	1,100+												
Shut	5.8	5.7	1,080+	Open	1,100	.45	5.12	15	1.364	4.0	1,201	61.2	80.5	2.3	
Open	.5	.4	1,095+	Shut	1,085	5.57					1,184	58.7	78.2		
Shut	5.8	5.6	1,085+												
Open	.5	.4	1,100+												
Shut	8.2	7.8	1,085												
Open	.5	.4	1,100												
Shut	8.7	8.3	1,075	Open	1,102	.45	7.86	24	2.18	6.4	1,203	61.6	80.8	3.5	
Open	.5	.4	1,105+	Shut	1,078	8.31					1,177	57.6	77.3		
Shut	8.6	8.3	1,075												
Open	.5	.4	1,100												
Shut	10.6	10.2	1,030+												
Open	.5	.4	1,095+												
Shut	10.8	10.5	1,025+	Open	1,102	.45	10.15	72	6.53	18.3	1,203	61.6	80.8	10.3	
Open	.5	.4	1,100+	Shut	1,030	10.60					1,124	50.3	70.5		
Shut	10.9	10.6	1,030+												
Open	.5	.4	1,105												
Shut	10.2	10.0	1,070												
Open	.6	.5	1,115												
Shut	10.8	10.4	1,065	Open	1,118	.55	9.90	51	4.56	13.1	1,220	64.2	83.1	7.5	
Open	.6	.5	1,120	Shut	1,067	10.45					1,164	56.8	75.6		
Shut	10.8	10.5	1,065												
Open	.65	.5	1,120												
Shut	10.9	10.5	1,050												
Open	.6	.5	1,120	Open	1,120	.55	10.22	69	6.16	17.4	1,223	64.7	83.5	10.1	
Shut	11.0	10.7	1,050+	Shut	1,050	10.77					1,147	53.4	73.4		
Open	.6	.5	1,120												
Shut	8.0	7.8	1,100												
Open	.6	.5	1,125+	Open	1,122	.55	7.47	21	1.87	5.5	1,225	65.0	83.7	3.1	
Shut	8.2	7.9	1,100	Shut	1,101	8.02					1,202	61.5	80.6		
Open	.6	.5	1,120												
Shut	5.5	5.3	1,110—												
Open	.6	.5	1,120—	Open	1,118	.55	5.00	10	.894	2.7	1,220	64.2	83.1	1.5	
Shut	5.8	5.6	1,110—	Shut	1,108	5.55					1,209	62.5	81.6		
Open	.6	.5	1,120—												
Shut	4.2	4.0	1,115												
Open	.6	.5	1,125	Open	1,123	.55	3.60	8	.713	2.1	1,226	65.2	83.8	1.2	
Shut	4.3	4.1	1,115	Shut	1,115	4.15					1,217	63.7	82.6		
Open	.6	.5	1,120												
Shut	2.1	2.0	1,115+												
Open	.6	.5	1,120	Open	1,120	.55	1.50	3	.268	.6	1,223	64.7	83.5	.6	
Shut	2.1	2.0	1,115+	Shut	1,117	2.05					1,219	64.1	82.9		
Open	.6	.5	1,120												
Shut	8.6	8.3	1,100												
Open	.5	.4	1,135												
Shut	9.2	8.8	1,110	Open	1,135	.50	8.3	29	2.55	7.4	1,239	67.3	85.6	4.4	
Open	.6	.5	1,135	Shut	1,106	8.80					1,207	62.2	81.2		
Shut	9.2	8.7	1,110—												
Open	.6	.5	1,135												
Shut	7.0	6.6	1,115												
Open	.5	.5	1,135	Open	1,138	.53	6.7	23	2.02	6.0	1,242	67.7	86.0	3.4	
Shut	7.3	7.0	1,115	Shut	1,115	7.23					1,217	63.8	82.6		
Open	.6	.5	1,140												
Shut	6.2	5.9	1,125												
Open	.6	.5	1,140	Open	1,140	.55	5.53	15	1.32	3.9	1,245	68.3	86.4	2.3	
Shut	6.3	5.9	1,125	Shut	1,125	6.08					1,228	65.5	84.1		
Open	.6	.5	1,140												
Shut	4.2	3.9	1,130—												
Open	.6	.5	1,140—	Open	1,139	.55	3.53	10	.88	2.6	1,243	67.9	86.1	1.4	
Shut	4.2	4.0	1,130	Shut	1,129	4.08					1,233	66.3	84.7		
Open	.6	.5	1,140												

TABLE I.—*Runs at constant throttle, varying back pressures*—Continued.

Observations.				Results. (Based on average of observations.)											
Position of end outlet valve.	Back pressure (inches of mercury).		Tachometer reading (r.p.m.)	Position of end outlet valve.	Average tachometer (r.p.m.)	Average back pressure (in. mercury).	Applied back pressure (in. mercury).	Speed change, not corrected (r.p.m.)	Percent speed change (max. r.p.m. =100 per ct.)	Percent power loss.	True speed (r.p.m.)	Brake horsepower.	Brake M. E. P. (pounds per square inch).	Loss of brake M. E. P. due to applied back pressure.	
	South side.	North side.													
Shut	2.0	1.9	1,135												Aug. 29, 1916
Open	.6	.5	1,140	Open	1,141	0.55	1.40	6	0.53	1.6	1,246	68.4	86.5	.9	
Shut	2.0	1.9	1,135	Shut	1,135	1.95					1,239	67.3	85.6		
Open	.6	.5	1,140+												
Shut	3.2	3.0	1,135												
Open	.6	.5	1,140	Open	1,139	.55	2.37	4	.352	1.0	1,243	67.9	86.2	.6	
Shut	3.1	2.4	1,135	Shut	1,135	2.92					1,239	67.3	85.6		
Oepn	.6	.5	1,135+												
Shut	4.3	4.2	1,135												
Open	.6	.5	1,140												
Shut	4.3	4.2	1,125												
Open	.55	.5	1,135	Open	1,137½	.54	3.71	12½	1.10	3.2	1,241	67.6	85.9	1.8	
Shut	4.3	4.2	1,115	Shut	1,125	4.25					1,228	65.5	84.1		
Shut	3.7	3.6	1,115												
Open	.5	.4	1,125												
Shut	3.9	3.8	1,115	Open	1,127—	.49	3.36	12	1.06	3.2	1,230	65.9	84.4	1.8	
Open	.5	.5	1,130	Shut	1,115	3.85					1,217	63.7	82.6		
Shut	3.9	3.8	1,115												
Open	.55	.5	1,125												
Shut	6.9	6.7	1,110—												
Open	.6	.5	1,130+	Open	1,127	.56	6.29	20	1.77	5.2	1,230	65.9	84.4	3.0	
Shut	7.0	6.8	1,105+	Shut	1,107	6.85					1,208	62.4	81.4		
Open	.6	.55	1,125+												
Shut	9.8	9.6	1,080												
Open	.6	.5	1,100+												
Shut	10.3	10.2	1,080	Open	1,109	.57	10.23	26	2.34	6.8	1,210	62.7	81.7	3.8	
Open	.6	.5	1,110	Shut	1,083	10.80					1,182	58.4	77.9		
Shut	10.4	10.2	1,090												
Open	.65	.55	1,115												
Shut	12.1	11.9	1,070												
Open	.65	.55	1,125	Open	1,123	.6	11.42	53	4.72	12.9	1,226	65.2	83.8	7.7	
Shut	12.1	12.0	1,070	Shut	1,070	12.02					1,168	56.3	76.1		
Open	.65	.55	1,120												
Open	.65	.45	1,125												
Shut	12.1	11.8	1,085+	Open	1,135	.59	11.48	49	4.31	12.4	1,239	67.3	85.6	7.3	
Open	.65	.50	1,140	Shut	1,086	12.07					1,185	58.8	78.3		
Shut	12.3	12.1	1,085												
Open	.7	.6	1,140												

TABLE II.—*Runs at varying throttle, back pressure conditions fixed.*

Back pressure conditions fixed, in the sense that the obstructions to the escape of exhaust gas were unchanged through the series of runs. However, the back pressure changed with engine power output due to change of amount of exhaust gas.

End outlet valve alternately open and closed, relieving or applying the back pressure.

Power output varied by changing the throttle position. These runs correspond to throttling an engine loaded by propeller with the exhaust escaping through a given manifold and muffler.

Data of Aug. 24, 1916, was obtained by forcing (by closing the end outlet valve) the exhaust to leak through the walls of a 4-foot length of 2½ inches flexible metallic exhaust hose and the joints of the connections.

Data of Aug. 29, 1916, was a similar set up with fewer leaks.

Observations.				Results. (Based on average of observations.)											
Position of end outlet valve.	Back pressure (inches of mercury).		Tachometer reading (R. P. M.).	Position of end outlet valve.	Average tachometer (R. P. M.).	Average back pressure (in. mercury).	Applied back pressure (in. mercury).	Speed change not corrected (R. P. M.).	Per cent speed change.	Per cent power loss.	True speed (R. P. M.).	Brake horsepower.	Brake M. E. P. (pounds per square inch).	Loss of brake M. E. P. (pounds per square inch).	
	South side.	North side.													
Shut	9.8	9.5	1,075												Aug. 24, 1916
Open	.55	.45	1,115	Open	1,115	0.53	9.30	43	3.81	11.0	1,217	63.8	82.5	6.2	
Shut	10.2	9.8	1,070	Shut	1,072	9.83					1,170	56.7	76.3		
Open	.6	.5	1,115												
Open	.35	.3	1,040												
Shut	7.00	6.6	1,000—	Open	1,042	.30	6.5	42	4.08	11.8	1,138	52.1	72.2	5.7	
Open	.30	.25	1,045	Shut	1,000	6.8					1,092	46.1	66.5		
Shut	6.90	6.7	1,000+												
Open	.15	.1	875												
Shut	3.6	3.6	850—	Open	875	.125	3.48	25	2.86	8.4	955	80.8	50.9	2.8	
Open	.15	.1	875	Shut	850	3.6					928	28.3	48.1		
Shut	3.6	3.6	850												
Open	.1	0	345	Open	345	.05	.175	0	0	0	377	1.9	7.9	0	
Shut	.25	.2	345	Shut	345	.225					377	1.9—	7.9		

TABLE II.—*Runs at varying throttles, back pressure conditions fixed*—Continued.

Observations.				Results. (Based on observations.)											
Position of end outlet valve.	Back pressure (inches of mercury). South side.	Back pressure (inches of mercury). North side.	Tachometer reading (R. P. M.).	Position of end outlet valve.	Average tachometer R. P. M.).	Average back pressure (in. mercury).	Applied back pressure (in. mercury).	Speed change not corrected (R. P. M.).	Per cent speed change.	Per cent power loss.	True speed (R. P. M.).	Brake horsepower.	Brake M.E.P. (pounds per square inch).	Loss of brake M.E.P. (pounds per square inch).	
Open	.05	0	525												
Shut	.6	.5	530	Open	530	.025	0.51	0	0	0	578	6.9	18.7	0.1	
Open	.05	0	530	Shut	530	0.54					578	6.8	18.6		
Shut	.55	.5	530+												
Open	.05	0	610−												Aug. 24, 1916
Shut	.8	.7	605+	Open	610	.025	.71	± 3	0.5	1.5	665	10.4	24.7	0.3	
Open	.05	0	610−	Shut	605+	.74					660	10.2	24.4		
Shut	.75	.7	605+												
Open	.4	.3	1,075												
Shut	9.2	8.8	1,050												
Open	.5	.4	1,110−												
Shut	9.6	9.4	1,060	Open	1,112	0.50	9.34	44	3.96	11.4	1,214	63.4	82.2	6.4	
Open	.7	.6	1,130	Shut	1,068	9.84					1,166	56.1	75.8		
Shut	10.6	10.4	1,080												
Open	.7	.6	1,135												
Shut	10.5	10.2	1,080+												
Shut	12.1	11.9	1,070												Aug. 29, 1916
Open	.65	.55	1,125	Open	1,122+	.6	11.4	+ 52	4.67	13.4	1,126	65.2	83.8	7.6	
Shut	12.1	12.0	1,070	Shut	1,070	12.0					1,169	56.5	76.2		
Open	.65	.55	1,120												
Shut	8.7	8.7	995												
Open	.3	.35	1,080												
Shut	8.7	8.6	995	Open	1,073	.33	8.34	78	7.27	20.3	1,171	56.8	76.5	10.7	
Open	.3	.35	1,060	Shut	995	8.67					1,086	45.3	65.8		
Shut	8.7	8.6	995												
Open	.35	.35	1,080												
Open	.15	.25	1,000												
Shut	6.8	6.8	940	Open	998	.20	6.68	60	6.01	17.0	1,089	45.7	66.2	7.7	
Open	.15	.25	1,000−	Shut	938	6.88					1,024	38.0	58.5		
Shut	6.8	6.7	940−												
Shut	4.3	4.3	830												
Open	.10	.1	860	Open	860	.10	4.25	30	3.49	10.1	939	29.3	49.2	3.4	
Shut	4.4	4.4	830	Shut	830	4.35					906	26.3	45.8		
Open	.1	.1	860												
Open	.10	.05	695												
Shut	1.80	1.80	680	Open	694	.06	1.72	14	1.98	5.8	758	15.4	32.1	1.4	
Open	.05	.05	690+	Shut	680	1.78					742	14.5	30.7		
Shut	1.80	1.70	680												
Shut	12.1	11.8	1,085+												
Open	.65	.50	1,140	Open	1,140	.60	11.47	54	4.74	13.5	1,244	68.1	86.4	6.0	
Shut	12.3	12.1	1,085	Shut	1,086	12.07					1,186	59.0	78.4		
Open	.7	.6	1,140												

TABLE III.—*Run with and without wire mesh muffler, varying throttle position, other conditions unchanged.*

[Runs of Aug. 29, 1916.]

Outlet conditions.	Back pressure (inches of mercury). South side (farthest from outlet).	Back pressure (inches of mercury). North side (nearest outlet).	Tachometer reading (R.P.M.).	Average back pressure (in. mercury).	True speed (R.P.M.).	Brake horsepower.
Muffler in position beyond quick-opening valve	0.02	0.02	730	0.02	797	17.9
	.03	.03	830+	.03	908	26.5
	.10	.10	930	.10	1,014	36.9
	.10	.20	1,020	.15	1,113	48.8
	.30	.35	1,100−	+.32	1,198	60.8
	.45	.45	1,140	.45	1,244	68.1
	.75	.65	1,170	.70	1,276	73.4
Without muffler	0	0	610+	0	668	10.6
	.02	.02	740	.02	808	18.7
	.07	.07	890	.07	971	32.4
	.10	.20	980	.15	1,069	43.2
	.25	.30	1,090	.275	1,190	59.6
	.40	.45	1,145	.425	1,250	69.1

TABLE IV.—*G. P. F. Mufflers; Throttle Varied.*

Mufflers placed one on the end of each straight exhaust manifold for each block of four cylinders of the Curtiss engine. One pair of the 28-inch long mufflers tested first, then the pair of 12-inch long mufflers were used.

[Sept. 8, 1916.]

TWO 28-INCH G. P. F. MUFFLERS.

Observations.						Results.									
Throttle position (hole No.).	Muffler on or off.	Back pressure (inches of mercury). South side.	Back pressure (inches of mercury). North side	Tachometer reading (R.P.M.).	Muffler on or off.	Average tachometer (R. P. M.).	Average back pressure (in. mercury).	Back pressure due to muffler (in. mercury).	Speed change due to muffler (R. P. M. not corrected).	Per cent speed change due to muffler.	Per cent power loss due to muffler.	True speed (R. P. M.).	Brake horsepower	Brake M. E. P. (pounds per square inch).	Loss of brake M. E. P. due to muffler.
4	Off	0.05	0	840	Off	850	0.01	0.63	0	0	0	928	28.3	48.1	0
	On	.6	0.06	850	On	850	.64					928	28.3	48.1	
	Off	0	0	860											
	On	.7	.65	850											
5	Off	0	0	970											
	On	1.5	1.50	980	Off	977½	.025	1.475	5	0.512	1.5	1,066	42.8	63.4	0.7
	Off	.05	.05	975	On	972½	1.5					1,060	42.1	62.7	
	On	1.5	1.5	975											
8	Off	0	0	1,160											
	On	4.0	4.0	1,140	Off	1,162½	0	4.0	26	2.24	6.6	1,268	72.1	89.7	3.9
	Off	0	0	1,165	On	1,136½	4.0					1,240	67.4	85.8	
	On	4.0	4.0	1,130+											

TWO 12-INCH G. P. F. MUFFLERS.

4	Off	0	0	850											
	On	0.25	0.25	855	Off	855	0	0.25	0	0	0	933	28.8	48.6	0
	Off	0	0	855	On	855	0.25					933	28.8	48.6	
	On	.25	.25	855											
5	Off	.05	0	980+											
	On	.55	.55	980+	Off	982	0	.55	0	0	0	1,071	43.4	64.0	0
	Off	0	0	980+	On	982	0.55					1,071	43.4	64.0	
	On	.55	.55	980+											
8	Off	0	0	1,150+											
	On	1.6	2.1	1,150−	Off	1,149	0	1.9	6	0.522	1.5	1,254	69.8	87.7	0.9
	Off	0	0	1,145	On	1,143	1.9					1,247	68.6	86.8	
	On	1.7	2.1	1,135+											

[1] Position for 75 H. P. as used in Table I.

TABLE V.—*Muffler tests on marine type, 4-cylinder two-cycle engine.*

B. H. P. of engine on these tests about 25. Exhaust noise about that of a 75 H. P. 8-cylinder 4-cycle airplane engine when exhaust was open.

Muffler.	Back pressure (inches mercury). With.	Back pressure (inches mercury). Without.	Back pressure (inches mercury). Due to muffler.	Speed (R. P. M.).	Remarks.
Variable pitch spiral	1.0±	0.75±	0.25	1,050–1,200	Noise over one-half stopped; exhaust still cracks a little. Back pressure very small; weight of muffler large.
One unit, "manifold muffler,"[1] end blocked; gas goes around end of inside cylinder.	1.30	.80	.50	1,200	Deadens sound more than spiral did.
One unit, "manifold muffler,"[1] end blocked; gas goes around end of inside cylinder.	.....	.....	.30	1,230	Muffler at end of long pipe through window to outdoors. Longer manifold before muffler may lower back pressure of muffler, but adds back pressure of its own that may be worse.
Two units of manifold muffler connected as designed.	.....	.....	.50	1,225	Back pressure same from either part of double set-up showing that it makes little difference whether gas goes around end of cylinder or not. Observed noise from distance of one-fourth mile, in direction to which open exhaust pointed. Noise strong when muffler was off, very like an airplane passing close overhead. Noise practically, but not quite, inaudible with muffler on. One could notice there was an engine somewhere, but the noise would not locate it.

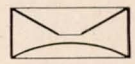
[1] Weight of one unit of "manifold muffler" about 4 pounds.

TABLE VI.

Muffler tests on Curtiss OX 8-cylinder, 4 by 5 inch motor, using whirl chamber mufflers. A check run on manifold muffler.
Notes on ability of mufflers to silence the crack of the exhaust taken on Ingeco single 5.5 by 10 inch cylinder farm engine, loaded and with retarded spark.

[Apr. 10, 1917.]

Muffler set-up, for all 8 cylinders.				Muffler off or on.	Back pressure (inches mercury).		Tachometer reading (r.p.m.)	True speed (r.p.m.)	Back pressure due to muffler.	Per cent power loss, from B. P. power loss curves.	Crack or bark suppression on Ingeco; general silencing ability; and remarks. (Fractions are reduction of noise, averages of estimates by 2 or more observers. Sketches show cross section of whirl chamber arrangements.)
Diameter of whirl chamber ring (inches).	Position of cone.	Position of cover plate.	Width of nozzle (inches).		South side.	North side.					
12	In	In	1	Off	0.5	0.10	1,140	1,245	1.2	1.0	½+off crack.
				On	1.6	1.5	1,140				
				On	1.6	1.4	1,140				
7	In	In	1	Off	.5	.1	1,130	1,234	1.5	1.2	½±.
				On	1.8	1.7	1,130				
				On	1.9	1.8	1,130				
7	In	In	.5	Off	.3	0	1,110	1,212	1.6	1.3	¾.
				On	1.9	1.65	1,110				
4	In	In	1	Off	.20	.05	1,100	1,201	1.55	1.25	⅓±.
				Off	.25	.05	1,100				
				Off	.30	.05	1,100				
				Off	.40	.05	1,100				
				On	1.8	1.6	1,100				
				On	1.9	1.6	1,100				
12	In	Out	1	Off	.40	.10	1,140	1,245	1.05	.85	½+.
				On	1.40	1.20	1,140				½+.
7	In	Out	1	Off	.40	.05	1,130	1,235	1.10	.90	½.
				On	1.45	1.2	1,130				
7	In	Out	.5	Off	.30	0	1,140	1,245	1.45	1.15	½+.
				On	1.7	1.5	1,140				
4	In	Out	1	Off	.30	.05	1,120	1,223	1.0	.83	½−, or less.
				On	1.2	1.0	1,120				
				On	1.3	1.15	1,120				
12	Out	Out	1	Off	.3	.2	1,130	1,235	−1.0	.8	⅔.
				On	1.35	1.10	1,130				
7	Out	Out	1	Off	.4	.05	1,110	1,212	−1.0	.8	½.
				On	1.3	1.1	1,110				
7	Out	Out	.5	Off	.3	0	1,190	1,300	1.45	1.15	¾; good muffling.
				On	1.7	1.6	1,190				
4	Out	Out	1	Off	.3	.05	1,100	1,201	.75	.63	Barks and whistles; bad.
				On	1.05	.80	1,100				
12	Removed.	Removed.	1	Off	.5	.05	1,130	1,234	.15	.12	
				On	.6	.25	1,130				
7	Removed.	Removed.	1	Off	.5	.05	1,100	1,201	.15	.12	
				On	.6	.25	1,100				
7	Removed.	Removed.	.5	Off	.5	.05	1,090	1,190	.27	.23	
				On	.75	.35	1,090				
4	Removed.	Removed.	1	Off	.45	.05	1,050	1,147	.15	.12	
				On	.50	.30	1,050				
Manifold muffler, one unit, as designed				Off	.5	.1	1,140+	1,247	.8	.65	¾.
				On	1.2	1.0	1,140+				
				On	1.35	1.10	1,110	1,212	1.0	.83	Good muffling.
				Off	.5	0	1,110				



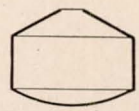


TABLE VII.

Tests of mufflers, continuing the investigations of capacity. First half of tests, mufflers taking exhaust from all 8 cylinders of Curtiss OX engine Second half of tests, mufflers taking exhaust from only 1 clock, 4 cylinders, north side of engine. Throttle position No. 8.

[Apr. 21, 1917.]

ONE MUFFLER ON 8 CYLINDERS.

Muffler and set-up, specifications of whirl-chamber mufflers.				Back pressure (inches of mercury).				Tachometer (multiply by 1.092 for true R. P. M.).		Back pressure due to muffler.	Remarks; sketches of whirl-chamber sections.
				Muffler off.		Muffler on.					
Ring diameter.	Cone.	Cover.	Nozzle width.	South.	North.	South.	North.	Off.	On.		
12	In.....	Out.....	1	0.10?	0.05	1.60	1.4	1,150	1,160	1.2	
12	In.....	Out.....	1	.4	.10	1.55	1.4	1,160	1,155	1.2	
7	In.....	Out.....	1	.40	.05	1.5	1.3	1,160	1,160	.9	
4	In.....	Out.....	1	.45	.10	1.3	1.1	1,160	1,155	.65	
Manifold muffler.....				.4	.1	1.0	.8	1,160	1,150		

ONE MUFFLER ON 4 CYLINDERS.

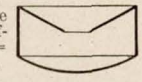
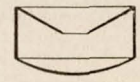
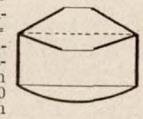
12	In.....	Out.....	1	.....	0.05	.....	0.6	1,140	1,140	0.55	
7	Shallow cone in.	Out.....	1	.....	.05	.....	.9	1,140	1,140	.85	Shallow cone fails to muffle Ingeco=¼ off bark. 
4	In.....	Out.....	1	.....	.05	.....	.7	1,140	1,140	.65	
Manifold muffler.....				.....	.05	.....	.7	1,150	1,150	.65	
7	Shallow = In.. Regular = Out Diffuser plate between.	Out.....	1	.....	.05	.....	1.0	1,150	1,150	.95	Ingeco muffling fair=½+; diffuser plate=sheet metal perforated with about 100 ⅛-inch holes. 

TABLE VIII.—*Tests of muffling qualities.*

Exhaust carried outdoors by connecting to the end of cross manifold two 6-foot lengths of 2-inch standard wrought-iron pipe, joined by a 45-inch cast-iron ell. This pipe caused 1 inch of mercury back pressure, additional, on the engine, but did not silence the exhaust noises. Curtiss engine. Throttle position No. 8.

The values of noise suppression were obtained from the collaborated estimates of a number of observers. One stationed in a direct line with the end of the exhaust pipe. Another at right angles to the line of the pipe, in the plane of the muffler. Another at the end of the pipe changing mufflers, and perhaps others scattered around. The first two were generally about 50 feet away from muffler, but other distances were also used when muffling qualities of two devices were nearly the same.

APR. 21, 1917.

Muffler and description.	Back pressure (inches mercury).				Tachometer (multiply by 1.092 for true R. P. M.).		Back pressure due to muffler.	Remarks, estimated bark suppression, in fraction or per cent.
	Muffler off.		Muffler on.					
	South.	North.	South.	North.	Off.	On.		
Manifold muffler, inside cylinder not touching end plate.	0.8	0.7	1.5	1.4	.....	1,150	0.7	½; steady swish, no crack.
12-inch whirl, cone in, cover out.....	1.0	.8	1.6	1.3	.....	1,150	.55	⅝; steady swish, less hum than manifold.
7 by 1 inch whirl, shallow cone in, deep cone out, no diffuser.	1.2	.8	1.8	1.7	.....	1,150	.75	¾; sharper crack.
4-inch whirl, cone in, cover out.....	1.2	1.0	1.5	1.5	.....	1,160	.4	⅜; very distinct crack.
Manifold muffler, end of inner tube closed, exhuast escapes only through holes in the tube (as designed).	1.2	1.0	1.9	1.7	.....	1,160	.7	⅞; can distinguish separate exhausts.
	.8	.6	1.4	1.5	.....	1,160	.75	¾; swish of explosions, hums steadily.
12-inch whirl, cone out, cover out.....	1.1	.9	1.5	1.4	.....	1,165	.45	½; more exhaust noise.
7 by 1 inch whirl, deep cone out, cover out..	1.2	.9	1.8	1.6	.....	1,165	.65	⅝; still more noise.
Manifold muffler, same as last.....	1.2	1.0	1.9	1.7	.....	1,170	.7	¾+, the loud cylinders scarcely audible.
MAY 12, 1917.								
Manifold muffler, tube end closed.....	0.9	0.8	1.6	1.6	1,170	1,170	0.75	80 per cent, light swish and hum.
G. P. F. 12-inch.....	1.1	1.0	3.2	3.0	1,170	1,165	2.05	80 per cent+; sharp swish.
7 by 1 inch whirl, venturi substituted for cone, cover out.	1.2	1.0	2.0	1.8	1,170	1,170	.8	50 per cent; metallic bark.
Manifold muffler, tube end closed.....	1.1	.8	1.85	1.7	1,140	1,140	.8	The different character of sound from G. P. F. and M. M. is hard to compare. Both are successful silencers.
G. P. F. 12-inch.....	1.25	1.0	2.9	2.7	1,135	1,130	1.7	
Manifold muffler, as last.....	1.05	.85	1.7	1.45	1,120	1,130	.6	
G. P. F. 12-inch.....	1.25	1.0	2.95	2.6	1,130+	1,130−	1.8	
Venturi (only).....	1.25	1.0	1.6	1.55	1,130	1,130	.5 +	Unearthly howl; loud shriek.
Manifold muffler, as last.....	1.2	1.0	1.8	1.6	1,145	1,145	.6	
Shell of manifold muffler, inner tube removed	1.2	1.0	1.9	1.6	1,145	1,145	.65	Roars and whistles.

TABLE VIII.—*Tests of muffling qualities*—Continued.

MAY 14, 1917.

Muffler and description.	Back pressure (inches mercury).				Tachometer (multiply by 1.092 for true R. P. M.).		Back pressure due to muffler.	Remarks.
	Muffler off.		Muffler on.					
	South.	North.	South.	North.	Off.	On.		
Duplex whirl, 1-inch entering nozzle	0.9	0.7	1.4	1.3	1,110	1,110		General conclusions fron tests of May 14, after repeated trials, were that the Duplex is slightly the better silencer than the manifold; both very good.
			1.3	1.1	.....	1,110	0.5	
Manifold muffler, regular	1.0	.8	1.6	1.3	.....	1,130	.6 —	
Duplex whirl, 1-inch entering nozzle	.....	.....	1.5	1.4	.....	1,110	.6	
...Do	1.1	.9	1.7	1.6	1,100	1,100	.65	
Manifold muffler, regular	1.3	1.0	1.8	1.7	1,100	1,100	.60	
Duplex whirl, ½-inch entering nozzle	1.3	1.0	1.8	1.7	1,110	1,110	.60	
Manifold muffler, regular	1.3	1.0	1.9	1.7	1,105	1,100	.65	
Manifold muffler, regular	1.2	.....	1.8	.....	[1]1,100	[1]1,100	.6	
Duplex, whirl 1-inch entering nozzle	1.2	.....	1.8	.....	[1]1,100	[1]1,100	.6	
Duplex whirl, ½-inch entering nozzle	1.2	.....	1.8	.....	[1]1,100	[1]1,100	.6	
Manifold muffler, regular	1.2	.....	1.8	.....	[1]1,100	[1]1,100	.6	

MAY 16, 1917.

Duplex whirl	1.0	0.75	1.6	1.4	1,125	1,125	0.65	Duplex whirl and long manifold muffler about equal in silencing; both good.
Long manifold muffler	1.1	.95	1.5	1.3	1,130	1,125	0.4	
Duplex whirl	1.2	1.0	1.7	1.5	1,125	1,125	.5	
Long manifold muffler	1.2	1.0	1.6	1.6	1,125	1,120	.5	

[1] About.

TABLE IX.—*Tests of muffling qualities.*

Various mufflers used. Otherwise apparatus same as that described in Table VIII. Tests made May 19 and 25, 1917, on Curtiss engine. Tests on Ingeco engine for bark suppression made on May 25, are shown in "Remarks."

Adam C. Davis, jr., C. A. Pierce, G. M. Rogers, H. Diederichs, V. R. Gage, G. B. Upton, and Birton N. Wilson individually made notes, and afterwards collectively made the final decision on the silencing qualities of the various devices.

MAY 19, 1917.

Muffler and description.	Back pressure (inches mercury).				Tachometer (multiply by 1.092 for true R. P. M.).		Back pressure due to muffler.	Remarks.	Weight (pounds).
	Muffler off.		Muffler on.						
	South.	North.	South.	North.	Off.	On.			
Duplex whirl, uniformly perforated diffuser, as before	1.0	0.8	1.4	1.2	1,050	1,050+	.....	These 3 mufflers all good silencers, G. P. F. judged best in respect to noise suppression.	3.0
	1.2	1.0	1.5	1.3	1,060	1,060	0.35		4.3—
Long manifold muffler	1.3	1.0	1.5	1.3	1,060	1,060	.25		4.3
G. P. F. 12-inch	1.2	1.0	2.8	2.8	1,060	1,060	.70		
G. P. F. 12-inch	.....	.....	2.9	2.8	1,065	.....	1.75		
12-inch whirl	1.3	1.0	1.5	1.4	1,060	1,060	.3	Slight roar, perhaps due to the light material used in construction.	3.4
Manifold muffler, regular	.9	.7	1.5	1.2	1,050	1,060	.5	Second best on swish; third on hum	4.6
Duplex whirl, graduated diffuser	1.1	.8	1.4	1.2	1,060	1,055	.35	First best on swish; second on hum	3.0
G. P. F. 12-inch	1.1	.8	2.2	2.0	1,045	1,040	1.2	Third best on swish; first on hum	4.3
Maxim	1.1	.8	2.9	2.8	1,110	1,110	1.9	Of these 3, Maxim judged best silencer, manifold muffler next, and G. P. F. last; all very good.	12.0
G. P. F. 12-inch	1.1	.8	2.3	2.0	1,125	1,110	1.2		4.3
Manifold muffler, regular	1.1	.8	1.5	1.3	1,120	1,120	.45		4.6

MAY 25, 1917.

New manifold, double inner tube	0.8	0.5	1.4	.....	1,140	1,140	0.4	New manifold muffler is much better silencer than G. P. F.	7.2
G. P. F. 12-inch	1.0	.....	2.0	.....	.....	1,130	1.0		4.3
	1.0	.....							
New manifold, single inner tube	1.0	.....	1.35	.....	1,145	1,145	.35	New manifold barks more without second inner tube. Now equals G. P. F. as a silencer. A short tail pipe on new manifold muffler does not change back pressure or silencing.	5.9
G. P. F. 12-inch	.9	.....	1.8	.....	1,140	1,140	.9		4.3

On Ingeco engine the new manifold muffler with two perforated inner tubes is easily better than G. P. F. 12-inch or the duplex whirl chamber mufflers.

TABLE X.—*Showing how the back pressure due to any one muffler apparently decreased as time passed. This effect is due to increasing leakage in the exhaust piping system.*

G = G. P. F. 12″ Muffler.
M = "Manifold Muffler" (regular).
L = "Long Manifold."
D = "Duplex Whirl Chamber."
12 = "Whirl Chamber," 12″.
7 = "Whirl Chamber," 7″ x 1″.

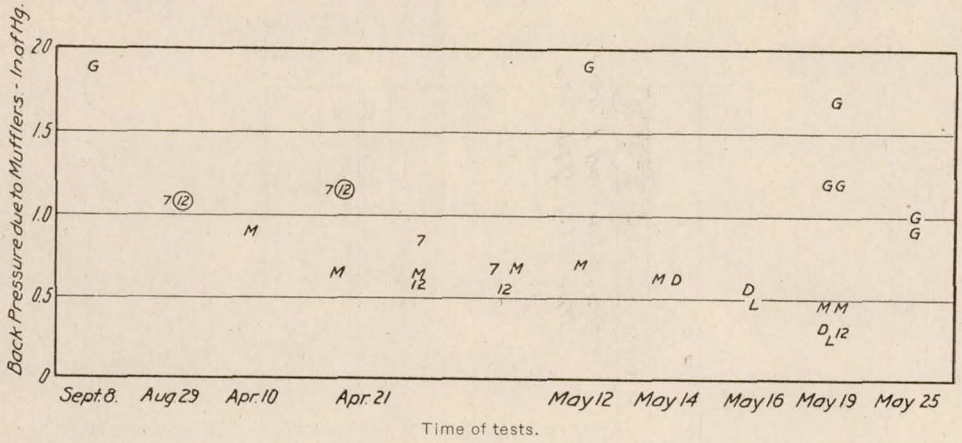


TABLE XI.—*Summary of results.*

Muffler.	Weight (pounds).	Curtiss, 8-cylinder, 70-horsepower.		Noise suppression estimated in per cent).	Silencing qualities.
		Back pressure (inches of mercury).	Power loss (per cent).		
G. P. F., 12-inch	4.3	2.0	1.6	75	Very good.
G. P. F., 28-inch	.....	4.0	3.2	40–70	Good minus.
Maxim (Ford)	12.0	3.6	2.9	75–80	Very good plus.
Manifold type	4.6	.8	.7	75	Very good.
Long manifold	.....	.7	.6	.....	Verygood.
New manifold:					
2 inner tubes	7.2	.8	.7	75–80	Very good plus.
1 inner tube	5.9	.8	.7	75	Very good.
Whirl chamber type:					
4-inch	1.2	.7	.6	30–40	Fair minus.
7 by ½ inch	1.8	1.0	.8	50–60	Fair plus.
7 by 1 inch	1.7	.8	.7	50	Fair plus.
12-inch	3.4	.8—	.6—	50–70	Fair plus.
Duplex	3.0	.8	.7	.....	Good plus.
Wire mesh	15.0	.3(?)	.2(?)	50	
Flexible metallic exhaust hose, 2 inches diameter	[1] 1	.....	.....	.....	
Curtiss stock manifold; 2 required	[2] 5.5	.....	.....	.....	

[1] Per foot of length.
[2] Each.

APPENDIX A.

FAN DYNAMOMETER DESIGN AND CALIBRATION.

Because of its flexibility and inherent regulation, due to torque varying as square of speed, and similarity to a propeller, the dynamometer chosen was the fan type. The general scheme of design is shown in figure 23. The resistance plates *PP* are of Tobin bronze plate $\frac{3}{16}$ inch thick. The length, a, of each plate parallel to the shaft is 14 inches. The radial width, b, of each plate is 10 inches. The plates are fastened to the steel arm, A, which revolves edgewise, by two angle irons riveted on the back of each plate, and bolted to the arm A. A series of evenly spaced holes in each end of arm A makes it possible to clamp the plates *PP* at any desired distances from the center, making the outside diameters of the plates, D_0, adjustable.

The fan shaft is mounted in ball bearings, which are supported by a framework built up of steel angle shapes. This frame is extended, as may be seen in the photograph, figure 1 of the main body of this report, to carry a rectangular box safety housing of wire mesh screen around the fan.

The design is copied in detail, both as to fan and framework, from a fan dynamometer at the A. C. A. testing laboratory in New York City, which in turn was built after the "Franklin" dynamometer. In each case the fan dynamometer of this design was tested out by driving

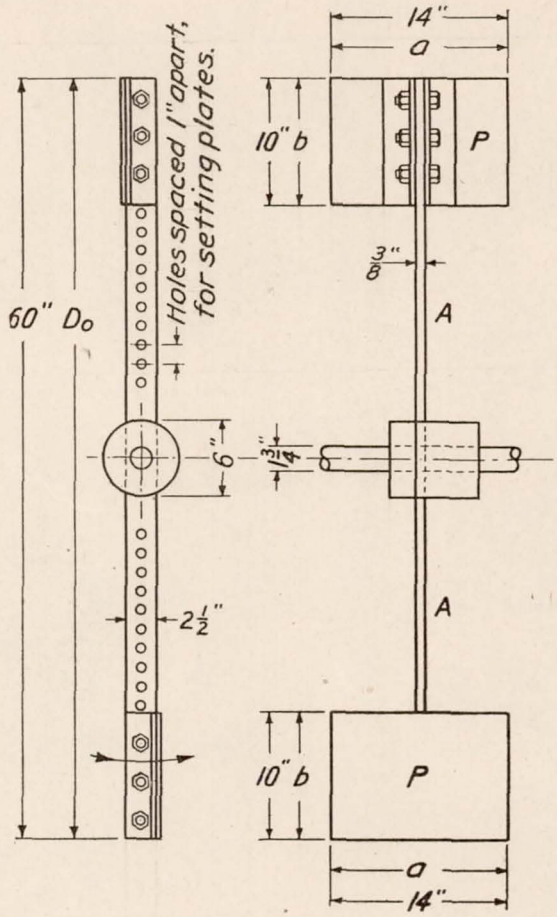


Fig. 23

from an engine or motor mounted on a cradle, and the calibration curves so obtained were available to us and used for our machine, as developed in the following analysis:

To check the accuracy of these calibrations we used the general formula for fan dynamometers, worked out by the White & Poppe Automobile Co., in England, and published in Automobile Engineer, August, 1910. The formula is quoted in the book on Dynamometers, by F. J. Jervis-Smith, on page 117. It is

$$HP = \frac{a^2 R^3 N^3}{4.01 \times 10^{15}}$$

in which a is the side dimension of a square plate, replacing the a and b of figure 23; $R = \frac{D_0}{2}$ of figure 23; and N = r. p. m. Dimensions were in centimeters in getting the constant 4.01×10^{15} above. We may generalize the formula into

$$HP = \frac{abD_0^3 N^3}{8 \times 4.01 \times 10^{15}}$$

for dimensions in centimeters, or

$$HP = \frac{2.54^5 abD_0^3 N^3}{8 \times 4.01 \times 10^{15}}$$

for dimensions in inches. This reduces to

$$HP = 3.43 \times 10^{-15} \times abD_0^3 \times N^3.$$

The formula is stated by White & Poppe to be valid only if there is no interference with in or out flow of air around the fan. If there is such interference, and less air is handled, the power is decreased below that given by the formula.

Taking the formula as

$$HP = K \times 10^{-15} \times abD_0^3 N^3,$$

we checked over the available calibrations of our dynamometer design by finding the values of K for different settings of D_0, and trying to account for variations by the expected interferences with air flow.

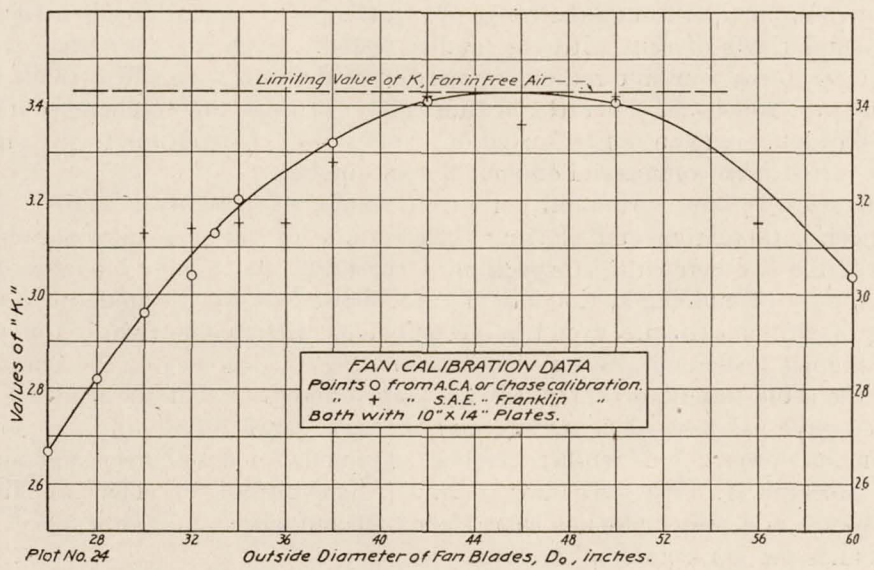
$$K = \frac{HP \times 10^{15}}{abD_0^3 N^3}$$

TABLE XII.—*S. A. E. or Franklin calibrations, 10 by 14 inch plates.*

Setting D_0	N	HP	K	Mean K
56	600	17.0	3.20	3.15
56	800	39.0	3.10	
50	800	30.7	3.43	3.42
50	1,000	60.0	3.42	
46	800	23.5	3.37	3.36
46	1,000	45.7	3.35	
42	1,000	35.5	3.42	3.42
42	1,200	61.5	3.42	
38	1,000	25.0	3.26	3.28
38	1,400	69.5	3.29	
36	1,000	20.7	3.17	3.15
36	1,400	56.2	3.14	
34	1,200	30.0	3.15	3.15
34	1,600	70.7	3.14	
32	1,200	25.0	3.15	3.14
32	1,600	59.0—	3.12	
30	1,200	20.0+	3.08	3.13
30	1,800	70.5	3.19	

TABLE XIII.—*A. C. A. calibration (Chase), 10 by 14 inch plates.*

Setting D_0	N	HP	K	Mean K
60	600	19.7	3.02	3.04
60	400	6.0	3.10	
50	700	20.4	3.40	3.41
50	500	7.5	3.43	
42	800	17.8	3.35	3.41
42	600	7.9	3.53	
38	900	18.1	3.23	3.32
38	600	5.8	3.49	
34	1,100	22.9	3.13	3.20
34	700	6.3	3.34	
33	1,100	20.8	3.11	3.13
33	800	8.2	3.18	
32	1,200	24.1	3.04	3.04
32	800	7.1	3.03	
30	1,300	24.5	2.95	2.96
30	900	8.2	2.98	
28	1,400	24.2	2.87	2.82
28	1,000	8.4	2.73	
26	1,600	27.1	2.69	2.67
26	1,100	8.6	2.63	



The relation of the K values to D_0, and of the two calibrations to each other, are shown in plot 24. The A. C. A. or Chase calibration seems probably the better, being notably more consistent internally. This may, however, be due to smoothing out of data by Chase, by cross-fairing methods. Low values of K for small values of D_0 are due to interference with intake air by the shielding framework around the fan; small values of K at large values of D_0 are due to interference of the floor and ends of framework with discharge air.

With given plate size and setting of D_0, we fix values of a, b, and D_0 of the formula $HP = K \times 10^{-15} abD_0^3 N^3$, and K is also fixed by the setting, so that the formula becomes for any one setting $HP = \text{constant} \times N^3$. Picking values of K from plot 24 for the 10 by 14 inch plates, assuming the curve sketched in along the Chase points as correct, we have:

TABLE XIV.

D_0	K	Constant$=(K\times10^{-15}\times10\times14\times D_0^3)$.
26	2.67	6.56×10^{-9}
28	2.82	8.66
30	2.96	11.2
32	3.08	14.1
34	3.19	17.6
36	3.26	21.3
38	3.32	25.5
40	3.38	30.2
42	3.41	35.4
44	3.42	40.8
46	3.42	46.6
48	3.42	52.9
50	3.41	59.6
52	3.37	66.2
54	3.31	72.8
56	3.23	79.3
58	3.15	85.9
60	3.04	91.8×10^{-9}

The "constant" gives the H.P. at 1,000 r.p.m. for each setting. The setting used throughout the muffler tests on the Curtiss engine was with $D_0 = 42$ inches, constant = 35.4 H.P. at 1,000 r.p.m.

APPENDIX B.

TESTS OF AUTOMOBILE ENGINE MUFFLERS AT UNIVERSITY OF MICHIGAN.

[Reported in Horseless Age, May, 1915.]

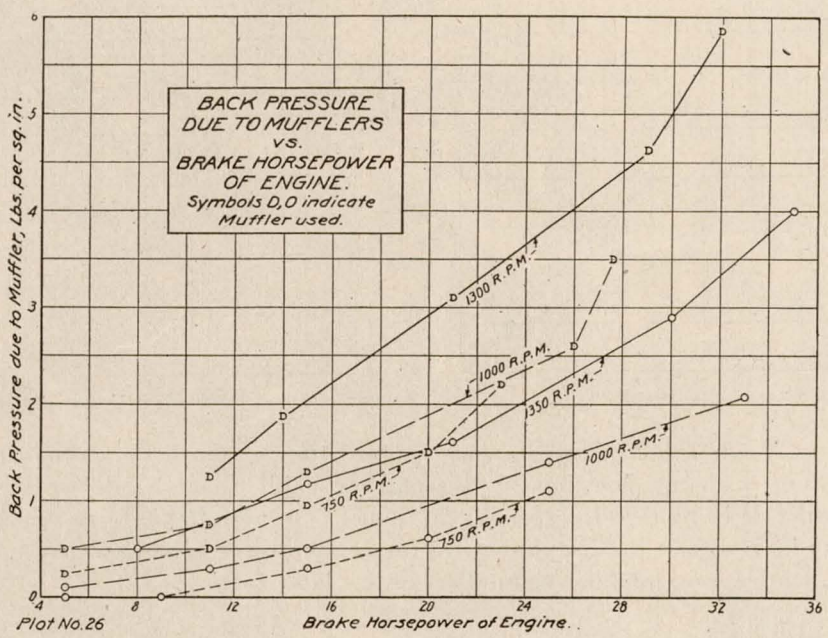
These tests were made on a stock Hudson 6-cylinder motor of 4⅛-inch bore by 5¼-inch stroke. For the purposes for which we would like to use the data the method of test was unfortunate. Runs were made through the range of throttle positions and speeds without a muffler, followed by similar sets of runs with the muffler tested. Back pressures were read with the mufflers. Power losses were inferred by comparison of the runs with and without the mufflers. As these runs were somewhat separated in time, power changes due to changes in carburetion, lubrication, ignition, etc., can not be sorted out from power changes due to the mufflers alone. The mufflers tested were commercial designs, five in number.

From the data we have sorted out parts from results on three of the mufflers (those found best as silencers), tabulating and plotting their results for our own information. The data are given in Table XV herewith. Inspection of the table, which may be taken to represent the state of the art of muffling at the date of 1915, shows how well grounded was the fear that the muffling of airplane engines would be accompanied with prohibitive loss of power. One commercial muffler lost about 18 per cent and another 14 per cent of the maximum engine power. At the same time, however, there was hope offered, in that the smallest and lightest muffler tested gave the best silencing and also the least power loss—only 3.6 per cent of the maximum engine power. This muffler weighed 14 pounds for a 40-horsepower motor, or 0.35 pounds per horsepower. We have now obtained, by contrast, excellent muffling on a 70-horsepower motor at a power loss less than 1 per cent and with a weight of 5 or 6 pounds (less than 0.09 pounds per horsepower).

TABLE XV.—*University of Michigan tests—Hudson 6, 4⅛ by 5¼ inches.*

Muffler.	750 r. p. m.					1,000 r. p. m.					1,300 r. p. m.				
	B.H.P. with muffler.	Back pressure with muffler (pounds per square inch).	H. P. loss.	Per cent power loss.	Loss of brake M. E. P. (pounds per square inch).	B. H. P. with muffler.	Back pressure with muffler (pounds per square inch).	H. P. loss.	Per cent power loss.	Loss of brake M. E. P. (pounds per square inch).	B, P. H. with muffler.	Back pressure with muffler (pounds per square inch).	H. P. loss.	Per cent power loss.	Loss of brake M. E. P. (pounds per square inch).
D	5	0.25	0.2	4.0	0.5	5	0.5	0.4	7.4	0.7	11	1.3	1.3	10.6	1.8
	11	0.5	0.2	1.8	0.5	11	0.75	0.5	4.3	0.9	14	1.9	1.8	11.4	2.5
	15	0.95	0.35	2.3	0.9	15	1.3	1.3	8.0	2.4	21	3.1	2.8	11.8	3.9
	20	1.5	1.0	4.8	2.5	26	2.6	1.6	5.8	3.0	29	4.6	4.6	13.7	6.5
	23	2.2	1.6	6.5	4.0	27.5	3.5	1.9	6.5	3.5	32	5.9	7.0	17.9	9.8
Y	5.5	0	0.1	1.8	0.25	5	0	0.05	1.0	0.1	10	0.2	0.05	0.5	0.07
	10.5	0	0.1	0.9	0.25	10	0.1	0.3	2.9	0.55	16	0.45	0.05	0.3	0.07
	16	0.2	0.3	1.8	0.75	15	0.2	0.3	2.0	0.55	19	0.6	0.5	2.6	0.7
	20	0.25	0.3	1.5	0.75	24	0.5	0.5	2.0	0.9	29	1.0	1.0	3.4	1.4
	24	0.5	0.9	3.6	2.3	31	0.9	0.6	1.9	1.1	38	1.1	1.4	3.6	2.0
O	5	0	0.1	2.0	0.25	5	0.1	0	2.0	0	[1] 8	0.5	0	0	0
	9	0	0.2	2.2	0.5	11	0.3	0.5	2.6	0.9	[1] 15	1.2	0.8	5.1	1.1
	15	0.3	0.1	0.7	0.25	15	0.5	0.8	5.1	1.5	[1] 21	1.6	2.5	10.6	3.4
	20	0.6	0.1	0.5	0.25	25	1.4	1.8	6.7	3.3	[1] 30	2.9	3.6	10.7	4.9
	25	1.1	0.6	2.3	1.5	33	2.1	0.9	2.7	1.7	[1] 35	4.0	5.6	13.8	7.6

[1] This group at 1,350 r. p. m.



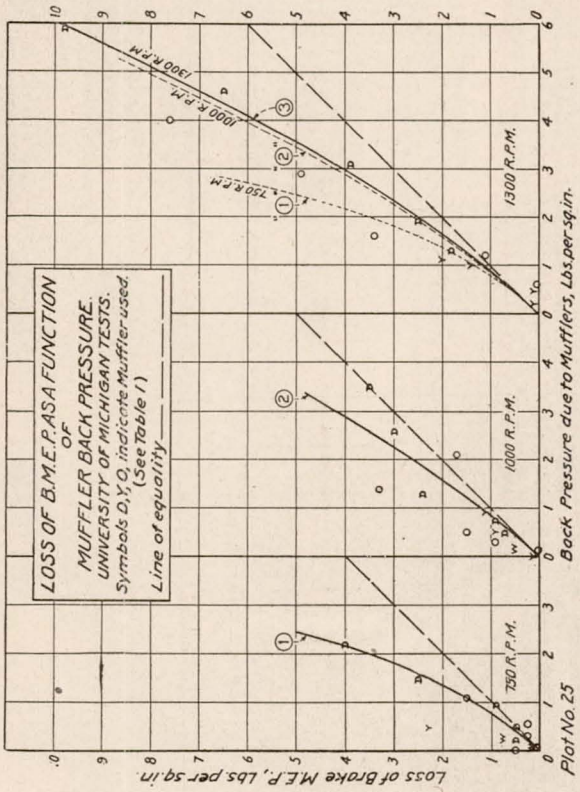
Muffler *Y*, besides giving the least back pressure and power loss, was the least in weight and size, and the best in silencing ability.

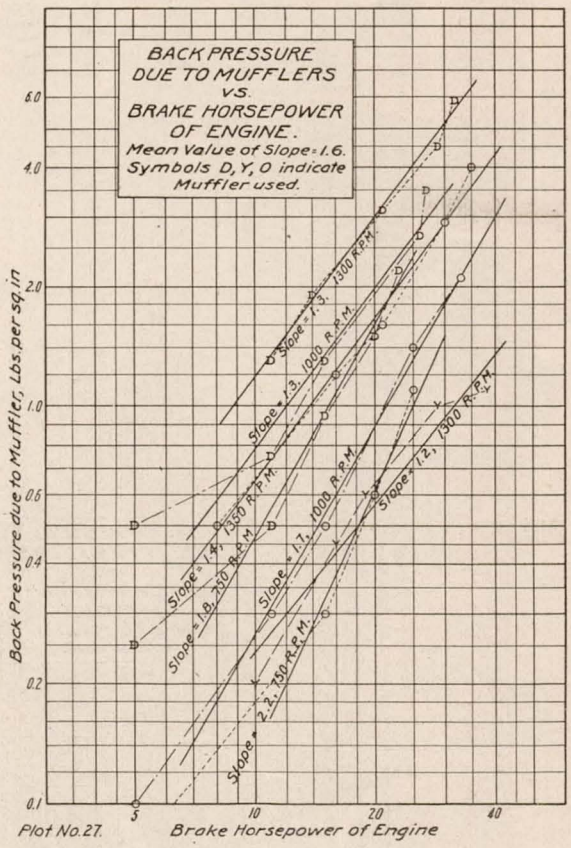
A partial analysis of the University of Michigan data is given in plot 25, showing the losses of brake M. E. P. as a function of back pressure at various speeds. At the right of plot 25 the curves for the three speeds are combined. The resultant grouping is comparable with Table II and plot 11 of the main body of this report. (Note that in plot 11 back pressures are in inches of mercury and in plot 25 in pounds per square inch.) The conclusions there reached are confirmed, at least qualitatively, from this independent source.

Plot 26 shows the back pressures due to the mufflers as a function of power output of the engine. It is similar to plots 7 and 12 of the main report. Plot 27 presents the same data in logarithmic plotting, just as plot 8 reproduces plot 7. The suggestion that back pressure varies as about the 1.5 power of the output of the engine is checked.

It does not seem quite true, however, that back pressure depends, for any one muffler and engine, solely on power output. The back pressure (and per cent power loss) is higher when

the power is obtained by small throttle opening and high speed than by large throttle opening and low speed. It should be remembered, however, that in the discussion of muffler capacity we have pointed out that some mufflers in our own tests did not increase back pressure when the number of cylinders exhausting into the muffler was doubled. Other mufflers did increase





back pressure under the same circumstances by 50 to 100 per cent; none quadrupled, as might be expected from ordinary flow laws. It seems probable that the differences between the curves for muffler *D* in plot 26 for speeds of 1,300, 1,000, and 750 r. p. m. are largely tied up with its having been a poor muffler design (in respect of power loss) and that such a difference would show much less with the better mufflers of our later tests.

REPORT No. 56

HEAT ENERGY OF VARIOUS IGNITION SPARKS

Part I.—METHOD OF MEASURING HEAT ENERGY OF IGNITION SPARKS

By F. B. Silsbee, L. B. Loeb, and E. L. Fonseca

Part II.—MEASUREMENT OF HEAT ENERGY PER SPARK OF VARIOUS IGNITION SYSTEMS

By F. B. Silsbee and E. L. Fonseca

Bureau of Standards, Washington, D. C.

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REPORT No. 56.

PART I.

METHOD OF MEASURING HEAT ENERGY OF IGNITION SPARKS.[1]

By F. B. Silsbee, L. B. Loeb, and E. L. Fonseca.

RÉSUMÉ.

This report describes a method developed at the Bureau of Standards for measuring the total energy liberated as heat in a spark gap by an ignition system. Since this heat energy is obtained from the electro-magnetic energy stored in the windings of the magneto or coil, it is a measure of the effectiveness of the device as an electric generator. It must be borne in mind, however, that this total energy is by no means a measure of the igniting power of the spark.

Use is made of a hollow block of copper and the sparks to be measured are passed between nickel alloy terminals in a cavity in the interior of the block. The heat liberated raises the temperature of the chamber and this temperature rise is measured by a copper-constantan thermocouple and a galvanometer. The apparatus is calibrated by sending a known current through a heating coil inclosed in the cavity. Measurements reliable to 5 per cent can be obtained in about 15 minutes as the apparatus is usually operated. The runs can be shortened to five minutes with some sacrifice of accuracy. A gap length 2.1 mm. (0.082 inch) between terminals 1.5 mm. (0.06 inch) in diameter is used, as this makes the breakdown voltage and duration of the spark substantially the equivalent of that occurring in an aviation engine cylinder.

INTRODUCTION.

The method for the measurement of energy dissipated in ignition sparks which is described in this report was developed at the Bureau of Standards as a part of the ignition investigation. It is recognized that this total heat energy is by no means a measure of the igniting power of a spark, since the latter is affected by many other factors. The value of this measure as an indicator of magneto performance arises from the fact that the energy which is liberated in the spark gap is derived from the electro-magnetic energy stored in the magneto or coil, and the amount of this energy is to that extent a measure of the effectiveness of the apparatus as an electric generator.

Calorimetric methods for measuring this energy have the advantages of greater simplicity and freedom from the many sources of error which are liable to enter into purely electrical methods of measuring power under the extreme conditions of high voltage and distorted wave forms which occur in ignition circuits. The use of a copper block form of calorimeter avoids the inconvenience of liquid calorimeters and has been found very satisfactory for this as well as many other lines of work. In common with other calorimeter measurements, the results can be conveniently expressed in absolute units and may therefore be compared with results obtained by other observers with different methods.

[1] This report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 15.

DESCRIPTION OF APPARATUS.

The calorimeter itself consists of a hollow copper block, as shown in figure 1, approximately 3.5 cm. (1.4 inches) in diameter and 5.5 cm. (2.2 inches) long, containing a cavity in the center. The spark to be measured occurs between the grounded electrode C and a high potential electrode B, the latter being insulated from the chamber by a small glass bushing. These electrodes are fitted with nickel alloy terminals 1.5 mm. (0.06 inch) in diameter, for most work set to give a spark gap of 2.1 mm. (0.082 inch). This gap may be varied, if desired, by the micrometer adjustment of the grounded terminal.

The effect of external temperature changes is compensated for by the use of a dummy copper block, E (figure 2), which is similar to the working calorimeter but contains no spark gap, and is placed symmetrically with respect to the working chamber inside of a double-walled wooden box. This box is lined with sheet copper in order to insure uniform temperature over its entire surface. A copper-constantan thermocouple has one junction imbedded in each of the blocks and by means of a Leeds & Northrup type 2,400 galvanometer serves to indicate the difference in temperature between the two blocks. The absolute temperature of either block is immaterial and is not measured. The galvanometer which has a sensitivity of 5 microvolts per division and a resistance of 190 ohms has been found very satisfactory for this purpose.

METHODS OF USE.

Starting with the two blocks at the same temperature the spark is passed in block A for two minutes and the magneto is then stopped for one minute to allow the temperatures to equalize. At the end of this third minute, the galvanometer is read and the magneto again started for another period of two minutes continuous run. This process is continued until five or six readings have been obtained. These galvanometer deflections are then plotted against time, giving a curve similar to the ones shown in plot 4. This curve is then superposed on the set of similar curves obtained at the original calibration of the instrument, and of which plot 3 is an example, and the average watts corresponding to the observed curves are read off directly. The heat energy per spark is then computed from the formula

$$\text{joules per spark} = \frac{\text{watts} \times 60}{\text{sparks per rev.} \times \text{r. p. m.}}$$

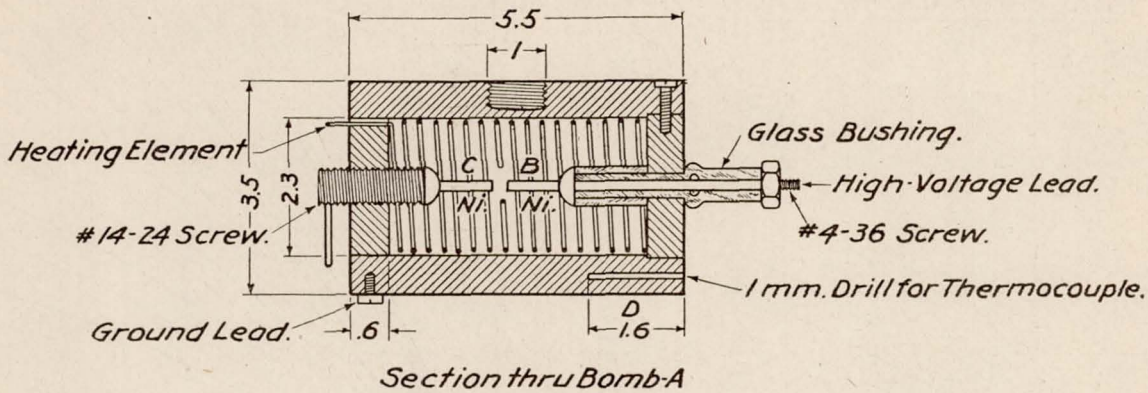
Before starting a second measurement, it is necessary to cool the chamber A to the temperature of the block B, but this is quite easily done by moistening it with alcohol and allowing this to evaporate.

The advantages of this somewhat complex system are that a number of galvanometer readings are obtained so that the results are not vitiated by a single error in reading, and the pauses between runs ensure that the temperatures are fairly equalized throughout the block. The time for the entire run is approximately 15 minutes. In cases where the dissipation of power is in excess of five watts, it is more convenient to use a cycle consisting of one minute running and one minute equalization.

It is, of course, possible to make a single continuous run of 5 or 10 minutes' duration and take a single galvanometer reading at the end of that time, and accuracy of 10 per cent or better can be obtained with such a procedure. It is also probable that apparatus of this general type might be constructed with mercury thermometers instead of a thermocouple and thereby avoid the necessity of using a sensitive galvanometer.

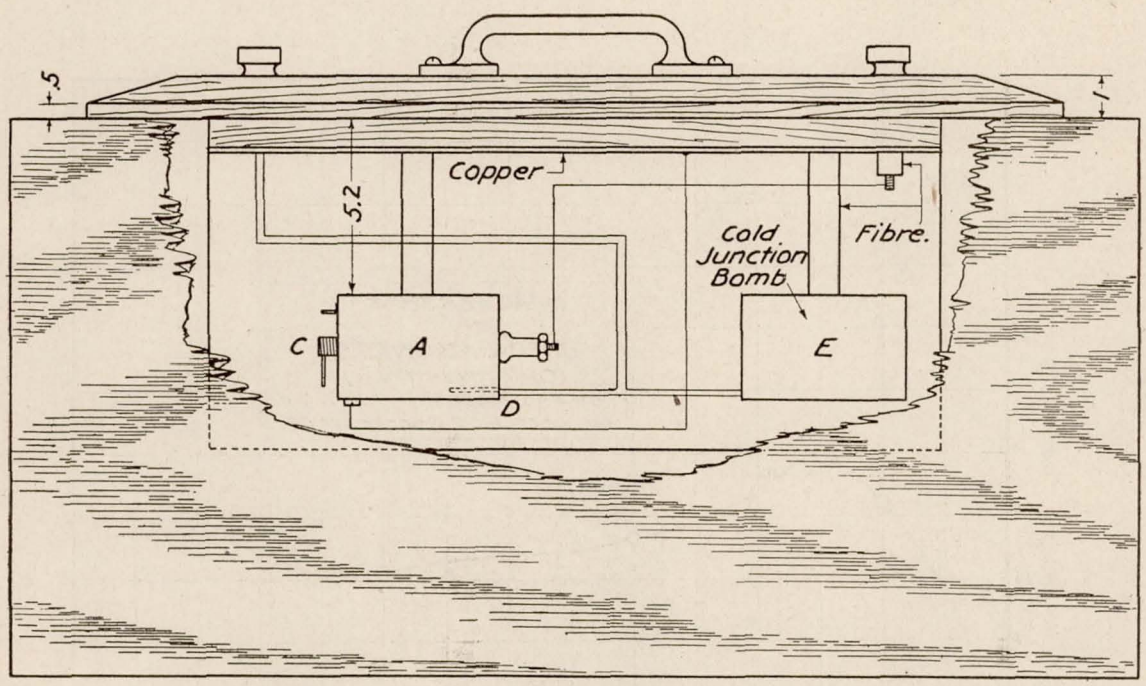
CALIBRATION.

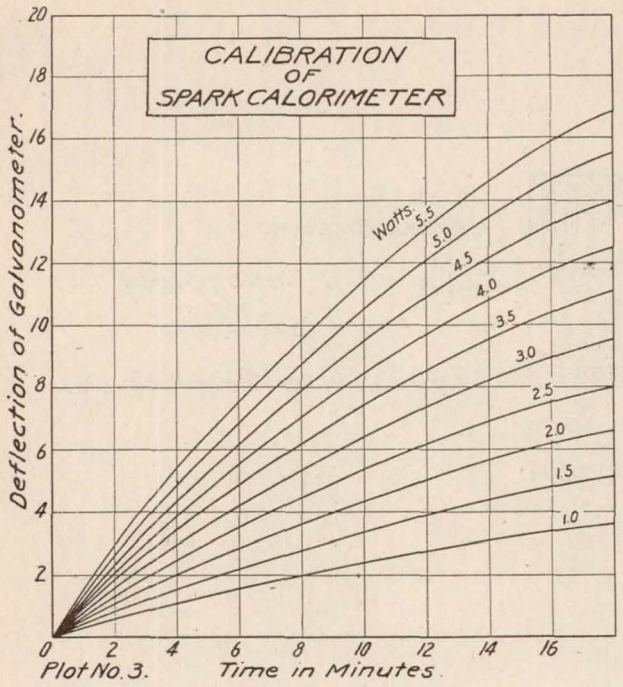
The calorimeter is calibrated by the use of a coil of resistance wire, which is shown in figure 1. A known amount of enery is dissipated in this coil using the same cycle of operation as is done in measuring the spark energy and the curves of galvanometer deflection against time are plotted as in plots 3 and 4. Since the heat is added at the same rate as in the actual operation, this method of calibration eliminates any error due to loss of heat from the calorimeter. The calorimeter has approximately a heat capacity equal to that of 40 grams of water, so that the temperature rise corresponding to 1,000 joules is about 6° C.



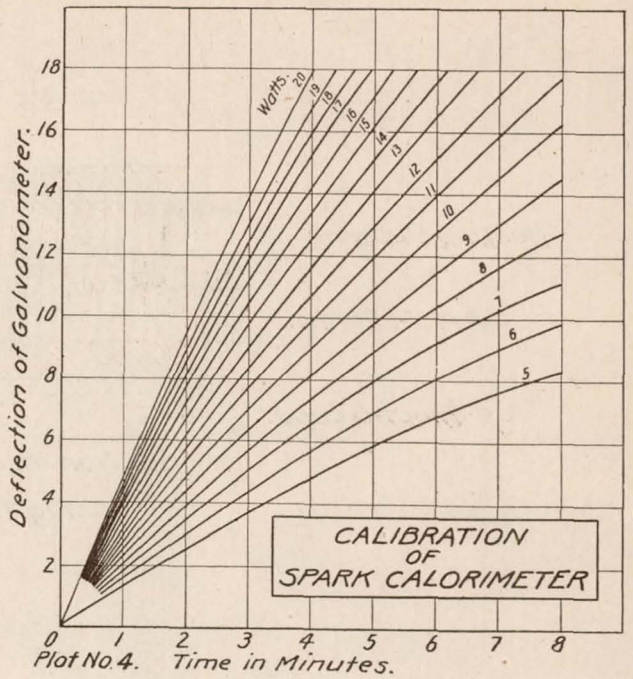
Section thru Bomb-A

Fig. 1.

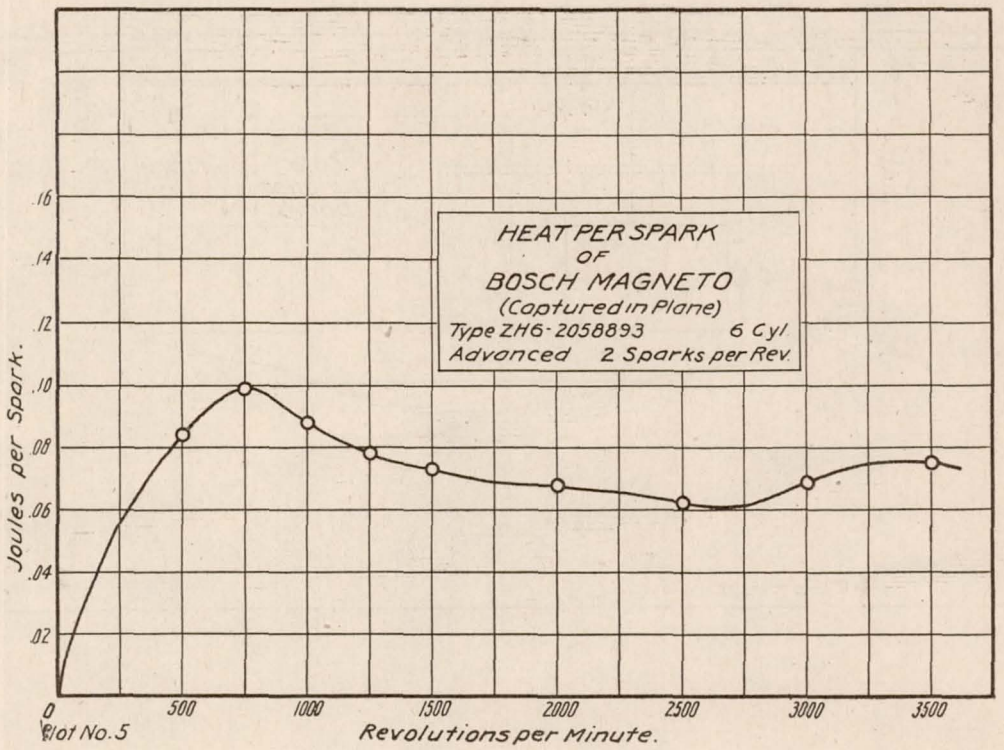




Plot No. 3.



Plot No. 4.



Plot No. 5

SOURCES OF ERROR.

As mentioned above, the heat losses from the calorimeter are compensated for by the use of the dummy chamber and the method of calibration. Another possible source of error is conduction of heat through the high-tension lead which is thermally insulated from the block by the glass bushing. This has been investigated by making use of the fact that if sparks of the same polarity are repeatedly passed through a gap, one electrode becomes much hotter than the other. Measurements were made on a system giving this constant polarity, both with the high-tension electrode as anode and later as a cathode, and no difference in average energy was detected. This indicates that the heat loss through the high-tension lead, even when the high-tension terminal is much hotter than it becomes with alternating sparks, causes no appreciable error.

The passage of the spark through the air causes a formation of oxides of nitrogen and nitric acid in the chamber which have some tendency to corrode the interior. Computations, however, show that the energy involved in these chemical reactions is entirely negligible in comparison with the heat energy dissipated. The change in volume of the gas, due to this chemical reaction, does not enter into the measurements with this apparatus as it does when an air thermometer is used.

The standard length of gap 2.1 mm. (0.082 inch) was chosen for this work because measurements with a crest voltmeter showed it to have the same breakdown voltage as that of an average spark plug in a high-compression engine cylinder. What is still more important, the voltage drop across the terminals while the spark continues to pass is also substantially the same as that occurring in an engine. This sustaining voltage is the principal factor in determining the rate of dissipation of energy and, consequently, the duration of the spark. Since the voltages above mentioned were measured with the gap in continuous operation, they include the effect of any accumulated ionization in the chamber, and therefore the fact that the gap is not ventilated is not an objection, but is, indeed, essential to the measurements for only under these conditions are the initial and sustaining voltages of the calorimeter gap the same as those obtaining in the average aviation engine.

It is believed that the results obtained with this apparatus and procedure may be relied upon to 5 per cent, and after the apparatus is once calibrated a determination can be made in about 15 minutes.

TYPICAL RESULTS.

Plot 5 gives a typical curve of the results obtained by this method on a shuttle core magneto at different speeds. The particular curve shown represents the performance of a Bosch Type Z–H–6 taken from a captured German airplane, and is quite similar to other high-grade magnetos. Battery systems usually give less heat, ranging from 0.01 to 0.03 joules per spark.

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REPORT No. 56.

PART II.

MEASUREMENT OF HEAT ENERGY PER SPARK OF VARIOUS IGNITION SYSTEMS.[1]

By F. B. Silsbee and E. L Fonseca.

RÉSUMÉ.

The duty of an ignition system is to produce definitely and reliably in the engine cylinder a spark sufficiently energetic to cause the rapid and certain combustion of the explosive mixture.

This report gives the results of direct measurements in absolute units of the total heat supplied to a spark gap by ignition systems of different types operating at various speeds under conditions substantially equivalent to those in the cylinder of a high-compression aviation engine. Values ranging from 0.16 joules (0.00015 B. t. u.) per spark in the more powerful magnetos to 0.03 joules (0.00003 B. t. u.) in the case of a battery system are recorded.

The actual igniting power of a spark depends on many factors which are at present little understood, and the total heat energy is by no means a direct measure of this igniting power. It does, however, give an index of the total power output of each type of machine, and forms a basis for a study of the effect of various features of design upon this output. Besides the systematic data given in the curves on plots 1 to 16, inclusive, and Table 1, additional measurements were made which showed that a condenser connected in parallel with the spark gap did not affect the heat liberated. The heat was also found to be independent of the gap length until this becomes so short that the spark lasts until the closing of the breaker. For still shorter gaps the heat dissipated becomes less.

INTRODUCTION.

When a spark discharge from an induction coil or high-tension magneto passes through a gas, a very appreciable amount of electrical energy is liberated which is rapidly dissipated as heat in the gas and to some extent in the electrodes. This heat energy is derived from the electromagnetic energy stored in the windings before the passage of the spark and the amount of this energy is to that extent a measure of the effectiveness of the device as an electric generator. Very little is known as to the detailed sequence of events by which the gas is ignited, and it is undetermined whether the ionization, which is always present, is an essential factor or whether the process is merely a thermal effect due to the high temperature resulting from the rapid dissipation of a relatively large amount of energy in a small space.

Recent experiments indicate that the total amount of energy required to explode a gaseous mixture (approximately 0.002 joules) is much less than that supplied by even a very weak ignition system of the conventional type. It is probable, however, that cases of faulty carburetion, where drops of fuel must be vaporized by the spark, require a discharge of very appreciable heat content. In such cases the larger volume and the longer duration of the hotter spark are also of value.

This report contains the results of calorimetric measurements of the energy content of the sparks produced under standard conditions by various types of ignition systems. The data

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 13.

are of value both as a general index of the power of each machine for comparative purposes and also as a basis for the more complete study of the effects of various features in design upon the delivered energy of a magneto.

Regular runs were made on 15 magnetos and one battery system for total energy output, the energy being measured on a specially constructed calorimeter described in a later paragraph. Observations were taken on the magnetos at speeds up to 3,500 revolutions per minute. Preliminary measurements have also been carried out to determine the effect of spark length and other variables on the total energy.

METHOD.

The calorimeter used is fully described in Part I of this report and consists chiefly of two hollow copper bombs of approximately the same shape and volume, suspended by means of hard rubber posts in a dead-air space. The spark is made to pass between nickel alloy spark points in the interior of one bomb and the rate of rise of temperature of this bomb over the other is measured by means of a thermocouple and galvanometer. Previous calibration with a known heater resistance and direct current provides means for determining the constant of the apparatus.

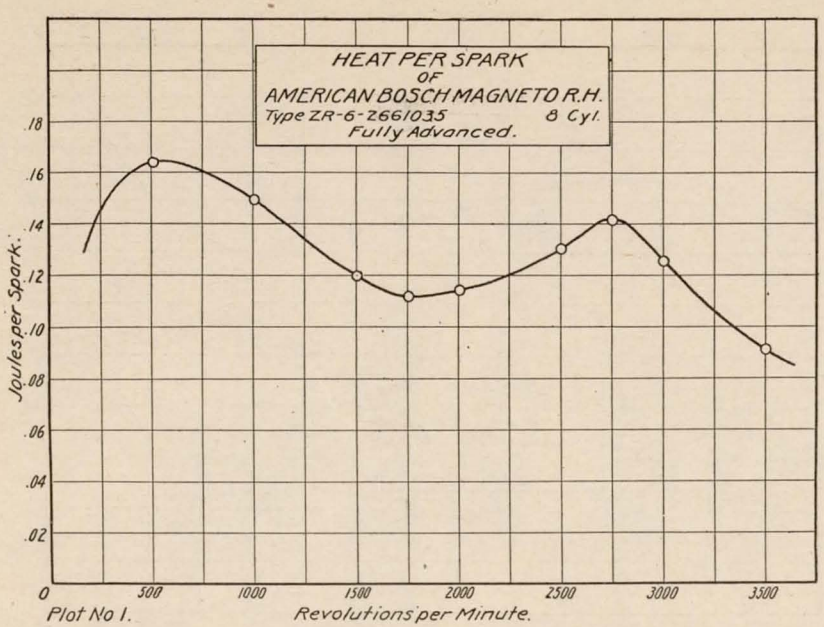
In the regular runs a standard spark length of 2.1 mm. (0.082 inch) between flat surfaces 1.5 mm. (0.059 inch) in diameter was used. This gap was chosen because it was found by measurement to have the same breakdown voltage (about 6,000 volts) as that of a 0.5 mm. (0.020 inch) gap between spark-plug electrodes in a high-compression aviation engine. Furthermore the voltage required to sustain the arc across these electrodes is approximately the same as that of an operating plug. Consequently the rate of dissipation of energy and the duration of the spark are substantially the same as in actual practice. A more detailed description of this method is given in Part I of this report.

REGULAR RUNS.

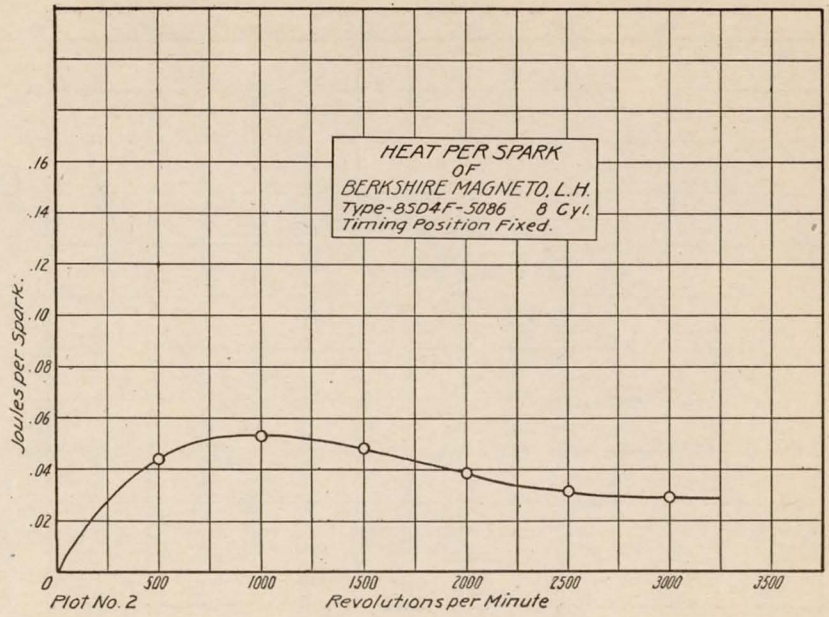
The principal features of each of the systems tested are tabulated in Table I, and the observed values of heat energy are plotted against magneto-driving shaft speed in plots 1 to 16, inclusive. Where the magnetos were provided with variable spark position, the measurements were made at full advance. The data from these plots are summarized in Table II. Column III gives the average joules per spark over the range from 500 to 2,500 revolutions per minute of the magnetos; column IV gives the maximum joules per spark, and column V the speed at which this maximum occurs; column VI gives the joules per spark at the speed required for operating at 1,500 revolutions per minute a 4-cycle engine of the number of cylinders for which the magneto is designed; column VII gives the joules per spark at the speed at which the system is delivering 100 sparks per second.

TABLE I.

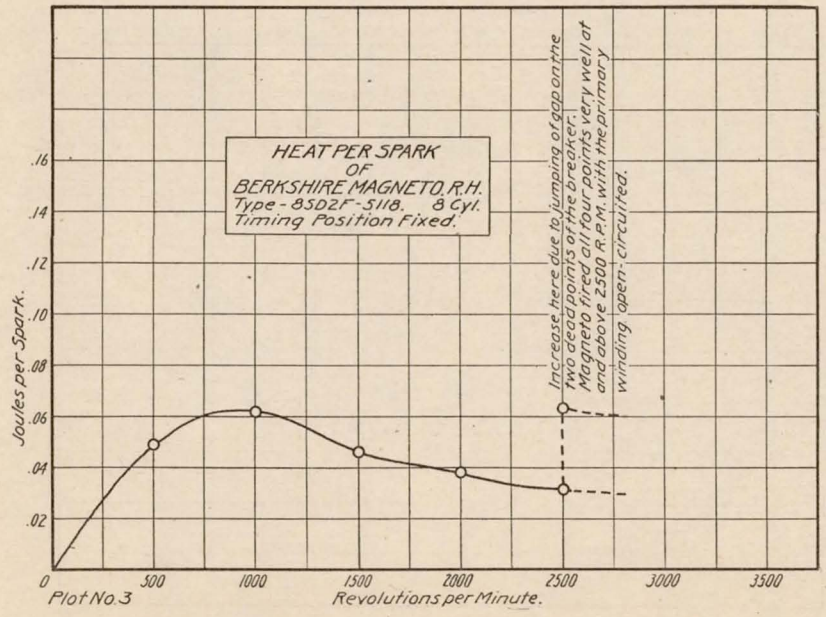
Plot No.	Name.	Model and Serial No.	Distributor.	Type.	Sparks per revolution.	Number of cylinders.
1	American Bosch	ZR-6, 2661035	Brush	Shuttle	2	6
2	Berkshire (left-hand)	8SD-4F, 5086	Jump	Inductor	4	8
3	Berkshire (right-hand)	8SD-2F, 5118	do	do	2	8
4	S. E. V. No. 1	H-8, 34167	Brush	Sleeve	4	8
5	S. E. V. No. 2	H-8, 27425	do	do	4	8
6	Berling	D 81 X 2, 65914	do	Shuttle	2	8
7	do	D 81 X 2, 65914	Jump	do	2	8
8	Lencke		Brush	do	2	4
9	American		do	do	2	8
10	Heinze (long cams)		None	Inductor	4	(12)
11	Dixie	800-19235, A-1432	Brush	do	4	8
12	Simms	SU-6, A-211741	do	Shuttle	2	4
13	Heinze (short cams)		None	Inductor	4	(12)
14	Liberty	D-5180-8073, Delco. 29788	Brush	Coil	12	12
15	German, Bosch	Z H 6, 2058893	do	Shuttle	2	6
16	B. T. H	A V-12s, 57531	Jump	Inductor	4	12



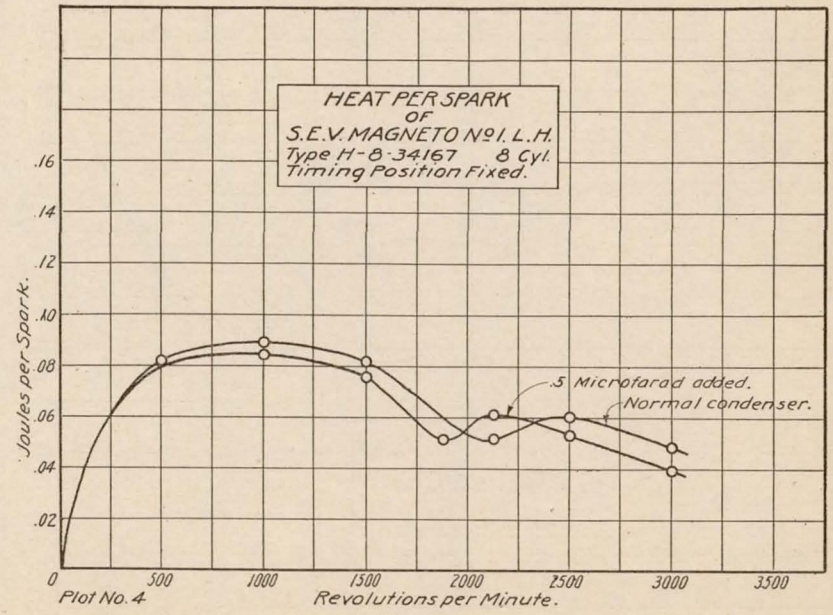
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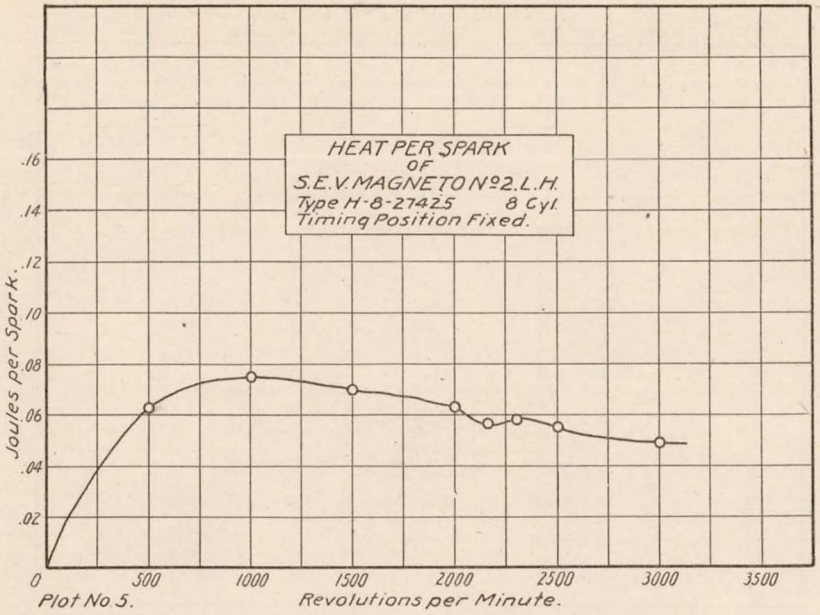
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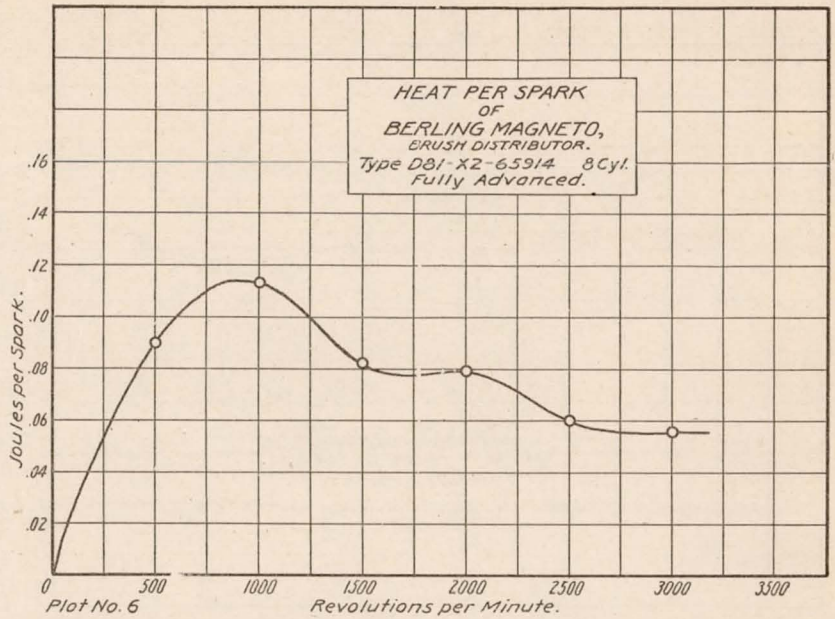
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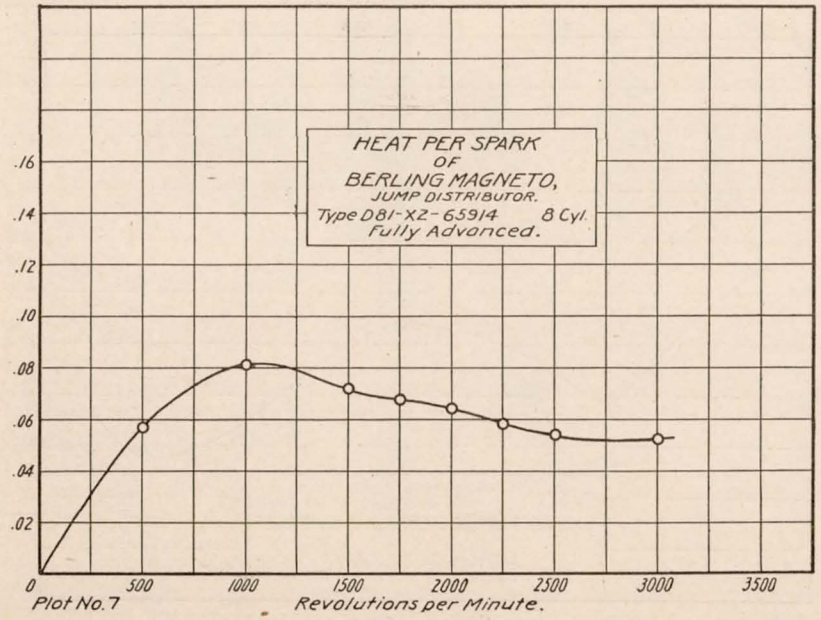
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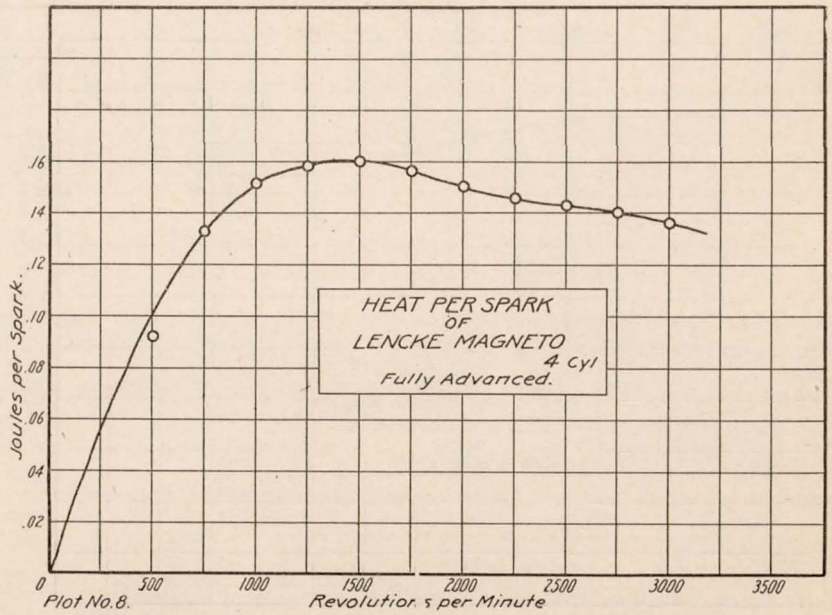
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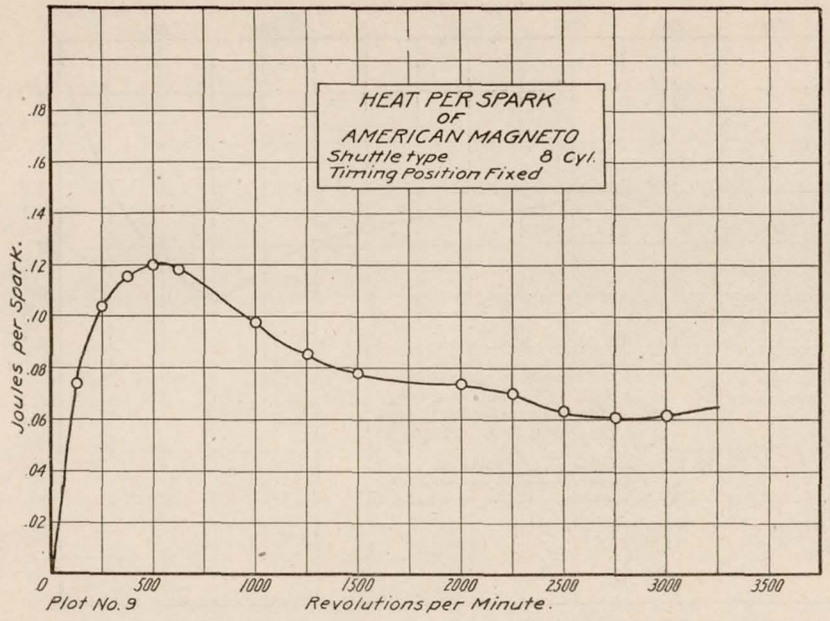
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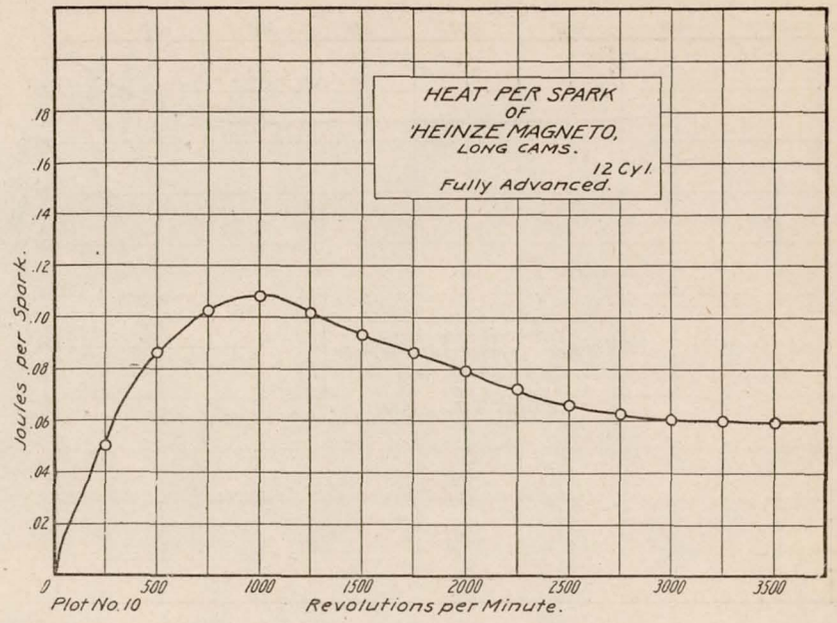
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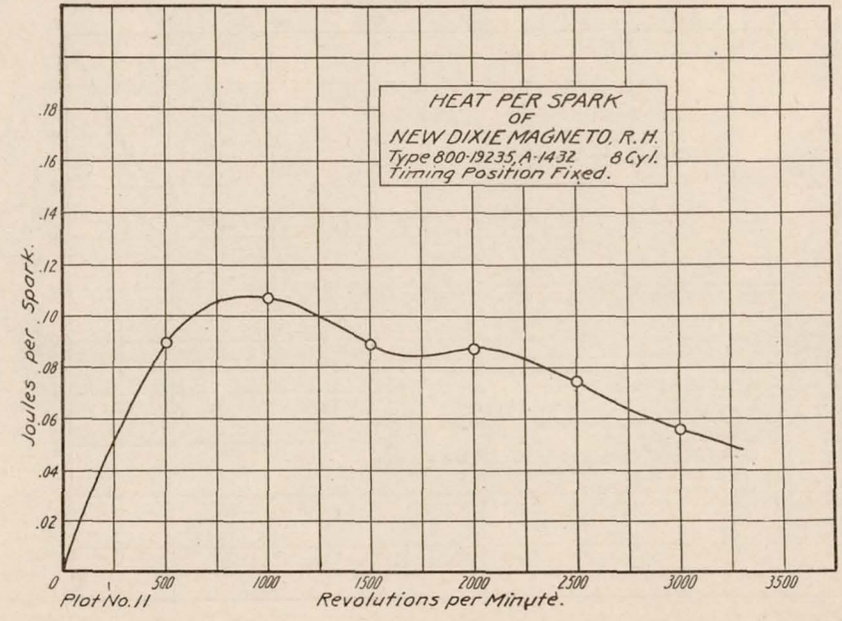
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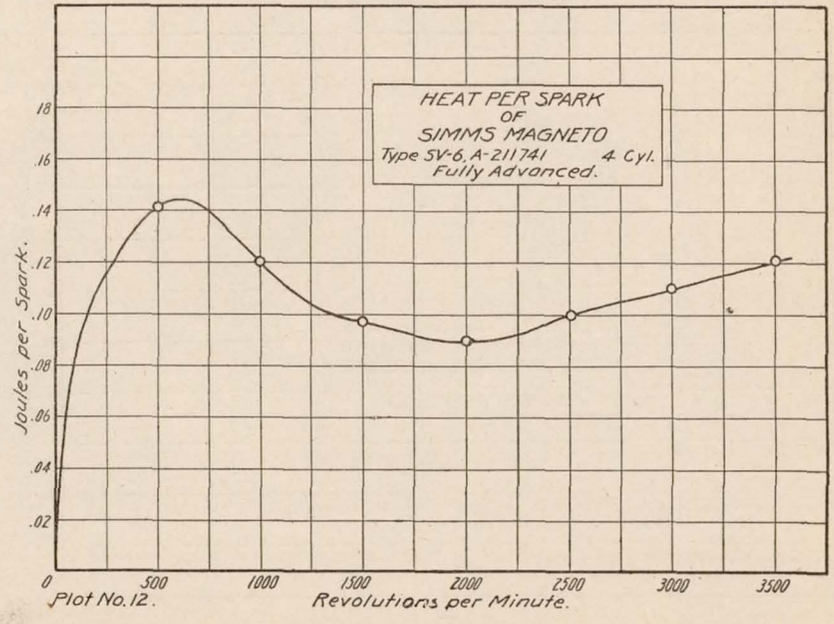
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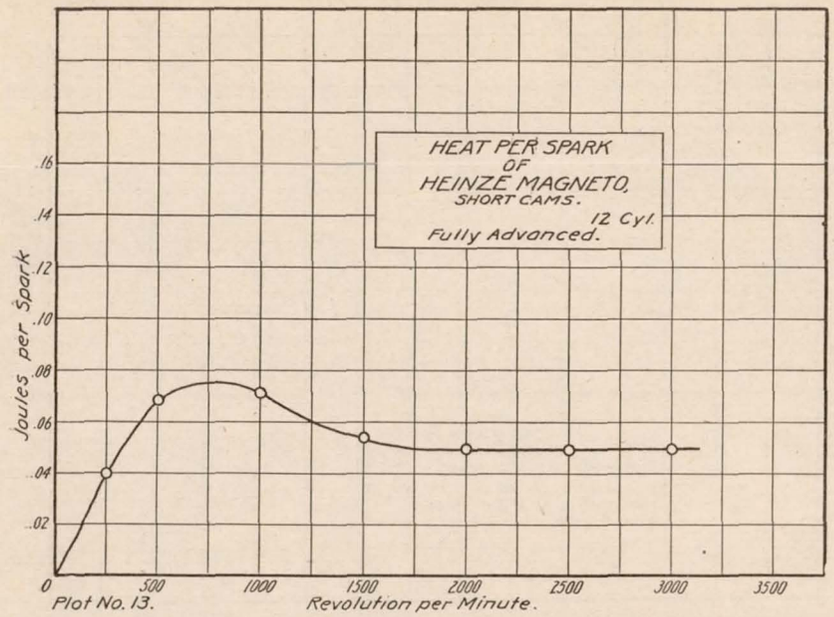
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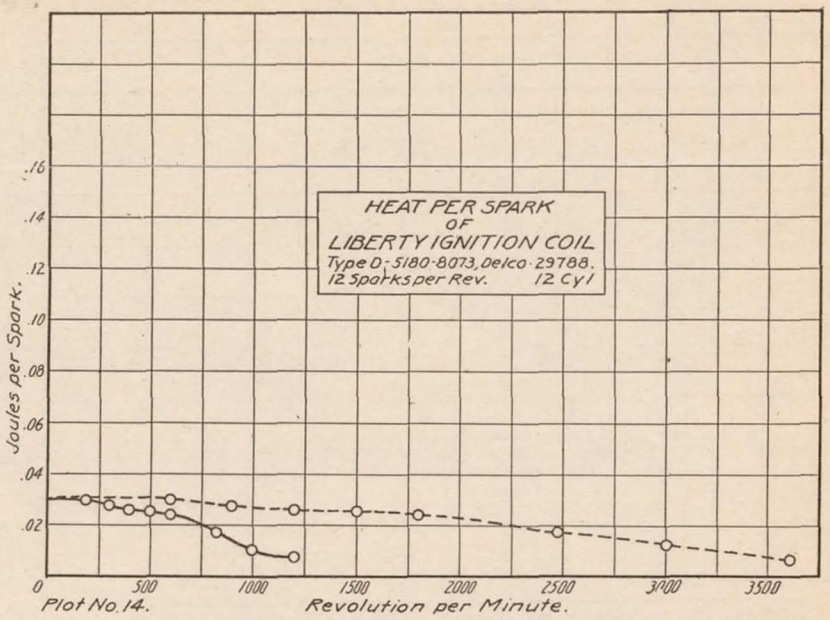
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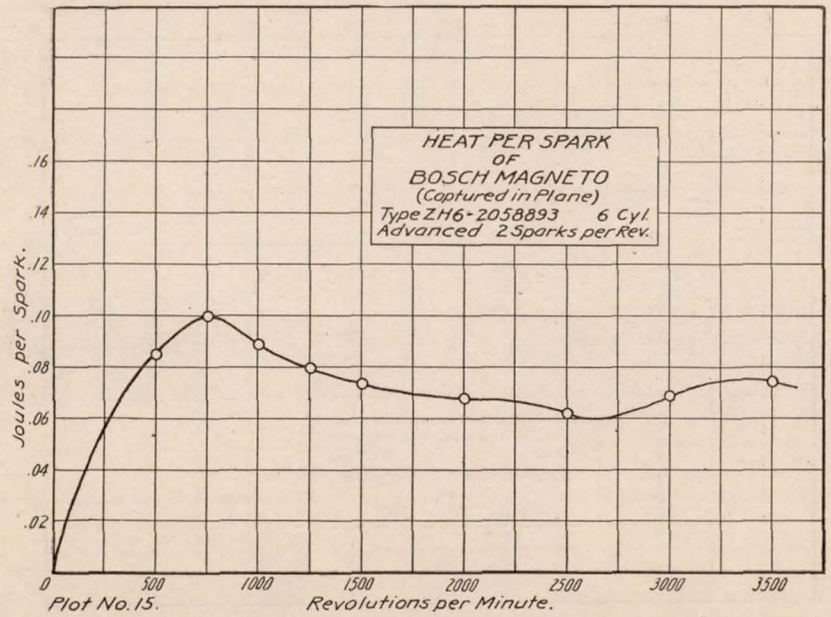
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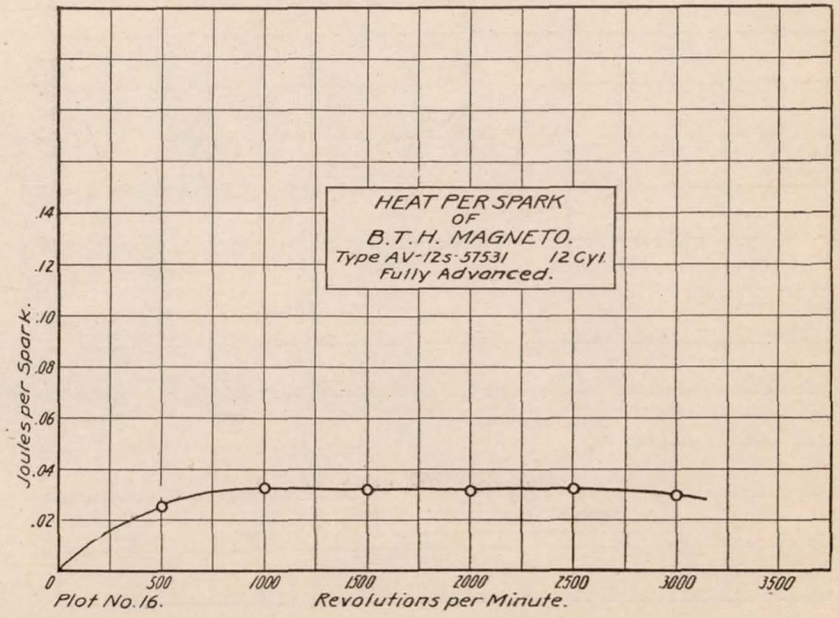
Plot No. 13.



Plot No. 14.



Plot No. 15.



Plot No. 16.

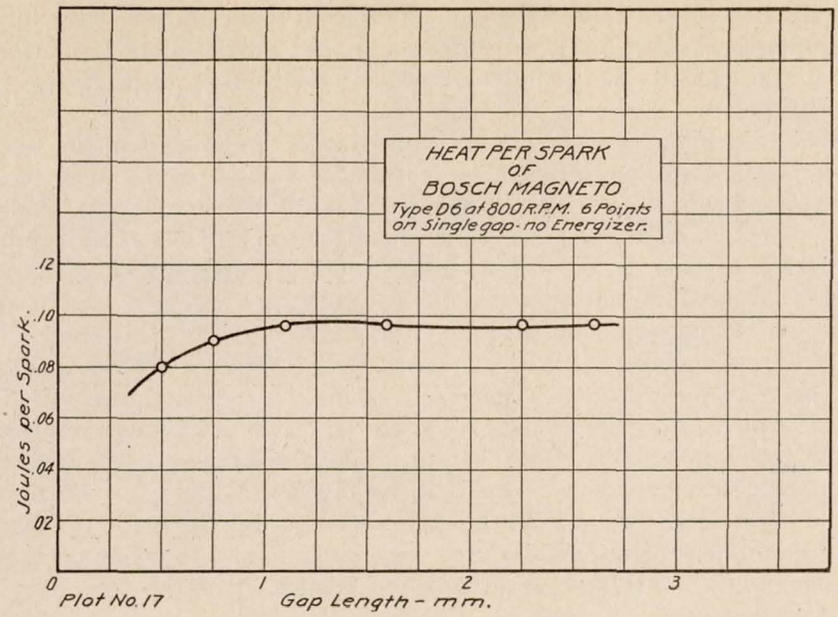


TABLE II.

I Plot.	II Magneto.	III Average joules/spark, 500–2,500 revolutions per minute.	IV Maximum joules/spark.	V Speed at maximum joules/spark.	VI Joules/spark at 1,500 revolutions per minute engine speed.	VII Joules/spark at 100 sparks/second.
1	American Bosch	0.132	0.165	575	0.121	[1] 0.128
2	Berkshire (left-hand)	.044	.054	900	.048	[2] .048
3	Berkshire (right-hand)	.047	.062	975	.028	[1] .030
4	S. E. V. No. 1	.074	.090	950	.082	[2] .082
5	S. E. V. No. 2	.067	.075	1,000	.070	[2] .070
6	Berling (Br.)	.089	.114	900	.056	[1] .056
7	Berling (J.)	.066	.082	1,050	.052	[1] .052
8	Lencke	.144	.160	1,450	.160	[1] .136
9	American	.086	.120	550	.062	[1] .062
10	Heinze (long cam)	.088	.108	1,000	.072	[2] .093
11	Dixie	.091	.108	925	.089	[2] .089
12	Simms	.110	.141	600	.098	[1] .111
13	Heinze (short)	.059	.075	775	.049	[2] .054
14	Liberty coil	.024	.030	Low speed.	.020	[3] .025
15	German Bosch	.077	.100	750	.066	[1] .068
16	B. T. H.	.031	.033	1,000	.032	[2] .032

[1] Corresponding magneto speed, 3,000 revolutions per minute.
[2] Corresponding magneto speed, 1,500 revolutions per minute.
[3] Corresponding distributor speed, 500 revolutions per minute.

It will be noticed that all the curves, with the exception of the Liberty battery and coil ignition set, have the the same general characteristic shape, rising rapidly to a maximum value at some low speed—generally between 750 and 1,000 revolutions per minute—then slowly decreasing toward higher speeds. In practically every case a peculiar bend in the curve, which is shown very markedly in plot 1, is evident.

The energy curve of the Liberty coil (plot 14) starts with its highest value at a very low speed and remains constant up to about 140 revolutions per minute. At higher speeds the primary current does not have time to build up to its maximum value, which causes a decrease in total energy as the speed is increased. In order to give a better comparison the coil system curve is replotted as a dotted line to correspond to the speed of rotation of a four-spark magneto. (The coil as operated gave 12 sparks per revolution.)

SPECIAL RUNS.

Several different runs were made on typical magnetos to determine the effect of (*a*) type of distributor; (*b*) condenser added to primary circuit; (*c*) large number of secondary turns; (*d*) length of spark gap; (*e*) added secondary capacity.

(*a*) A D–81 Berling magneto with demountable distributors was used to determine the effect of the jump-spark distributor as compared to the brush; plots 7 and 6 show the total heat curves of this magneto with the two types of distributor, respectively. Although the general shape of the two curves is the same, the energy obtained with the jump-spark distributor is about 10 per cent less than that obtained with the brush over the whole range.

(*b*) It is not definitely known whether the depressions occurring in all the curves are of electrical or mechanical origin. Plot 4 shows a very interesting point that was brought out on the curve for S. E. V. No. 1. A 0.5 microfarad paraffined paper condenser was put across the primary breaker in parallel with the original condenser of about 0.2 microfarad in the magneto. This additional capacity did not alter the running condition as far as sparking at the breaker points was concerned, but the whole curve of heat energy, together with the position of the depression, was moved toward the origin by a definite amount. It should be noted that none of the maximum or minimum points in the curves was raised or lowered.

(*c*) Plot 3, which shows the energy curve for a two-spark-per-revolution Berkshire magneto of the inductor type, is also of interest. This machine gives four flux reversals per revolution, but the primary breaker cam is so arranged that only two breaks are made per revolution, and, therefore, but two of the flux reversals are used. This magneto is wound with a very large number of secondary turns, and it was found that beyond 2,500 revolutions per minute, due to the large voltage of rotation generated in the secondary winding, four sparks occur per revolution. By leaving the primary circuit open, four sparks per revolution were obtained at all speeds above 2,500 revolutions per minute. This accounts for the apparently increased heat per spark obtained at the higher speeds. The Dixie 12-cylinder and the Heinze 12-cylinder magnetos also generated sufficient rotation voltage to break down a 5-millimeter (0.2 inch) spark gap in air.

(*d*) Plot 17 shows the effect of increasing the calorimeter spark gap. These runs were made using a type D–6 Dual Bosch magneto, firing all points through the distributor. The readings were taken at a constant speed of 800 revolutions per minute. The heat per spark increases in value up to a 1.2-millimeter gap, beyond which it stays practically constant. The slope of the curve toward zero is probably due to the fact that with small gaps the sustaining voltage is low, the duration of the spark is correspondingly long, and the closing of the breaker quenches the spark before the full amount of available energy has been expended. The average secondary current also is larger with a short gap, and, therefore, the I^2R loss is greater and the spark energy less.

Plots 10 and 13 show the effect of the length of cam (i. e., the angle during which the primary breaker is held open). In plot 13 the breaker closes before the spark has had time to dissipate all the available energy. This both decreases the fraction of the total stored energy which is liberated in the gap and also interferes with the building up of current for the next spark, so that the available energy is also reduced. In plot 10 a similar magneto with longer cams, which prevent this interference, shows nearly 50 per cent greater spark energy.

Several runs were made at constant speed on the Bosch D–6 magneto, with a condenser of 0.0017 and 0.0034 microfarad capacity placed across the calorimeter gap. It was found that this caused no appreciable change in the total energy of the spark, but the discharge was changed from a more or less flaming arc to a snappy white spark.

REPORT No. 57

THE SUBSIDIARY GAP AS A MEANS FOR IMPROVING IGNITION

BY

W. S. GORTON

Bureau of Standards, Washington, D. C.

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REPORT No. 57.

THE SUBSIDIARY GAP AS A MEANS FOR IMPROVING IGNITION.[1]

By W. S. Gorton.

RÉSUMÉ.

This report was prepared at the Bureau of Standards for the National Advisory Committee for Aeronautics.

Additional or subsidiary gaps have frequently been used in jump-spark ignition systems, in order to cause the resumption of sparking in fouled spark plugs. The series gap, to which the greater part of this report is devoted, is a subsidiary gap in the connection between the high tension terminal of the plug and that of the magneto or coil. A brief account is given of the use of this gap up to the present time and also of the statements concerning it which have gained some currency, most of which are shown to be erroneous. The simple theory of the action of the series gap is discussed and a detailed account given of the effect upon the sparking ability of the plug produced by changes in the values of the electrical resistance of the fouling and of the capacities in parallel with the plug and with the magneto or coil. Experiments confirm the main features of the simple theory. The points of difference between the conditions as postulated in the simple theory and the conditions actually existing are enumerated and their bearing upon the design and operation of the series gap discussed. The ensuing section is devoted to a discussion of the design of series gaps.

It is concluded that the series gap may be used as a remedy for a considerable part of the trouble due to the fouling of plugs which is met with in practice, since it has been found possible by the use of a series gap on an average ignition system to spark a plug having a fouling resistance of only 4,000 ohms.

INTRODUCTION.

The spark plugs used on internal combustion engines employing the jump-spark system of ignition are subject to many ills. At present the chief of these is the fouling of the plugs with carbon and oil, which are deposited on the surface of the insulation forming a conducting path between the electrodes of the plug. The resistance of this path frequently falls so low that sparks will no longer pass between the electrodes. It has been found that, under these conditions, modifications of the ignition system involving the use of an additional spark gap, or gaps, will cause sparks to pass again between the electrodes. Such spark gaps are called subsidiary gaps and the use of them will be discussed in this report.

Some of the ignition systems employing subsidiary gaps have been of designs radically different from those ordinarily used. In the majority of cases, however, the use of a subsidiary gap has involved merely the insertion of a gap in the connection between the high-tension terminal of the magneto or coil and that of the spark plug. Such a subsidiary gap is called a series gap, and it is with this gap as opposed to the other varieties of subsidiary gaps that this report principally deals.

The series gap has been made in many forms and employed in numerous ways. A large number of claims, frequently of an extravagant character, have been made in its favor, while there have also been objections raised against the use of such devices.

The purpose of this report is to make available, in a form convenient for reference, the more important information concerning series gaps, and to state what may reasonably be expected

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 31.

of them, in order to avoid either undue optimism or pessimism concerning their usefulness. To these ends the present report comprises:

(A) A statement of the past and present state of "the art."
(B) A summary of our present knowledge of the action of series gaps.
(C) Design of the series gap.
(D) An estimate of the degree of utility which may reasonably be expected of series gaps.

(A) PAST AND PRESENT STATE OF THE ART.

In the automobile field racing drivers have long used the series gap for improving the ignition of their cars. In its original form it consisted simply of a block of wood fastened to the spark plug. To this block was attached the high tension lead in such fashion that there was a small gap between the end of the wire and the terminal on the insulated electrode of the spark plug.

Recently various commercial forms of the series gap, usually intended for attachment to standard spark plugs, have appeared. Those of American manufacture that have come to the attention of this bureau are as follows: (*a*) Master, (*b*) Speco, (*c*) Superspark, (*d*) Walden Worcester.

The Master and Superspark devices may very well be described together as they are similar in construction. In each device the series gap is inclosed in a steel container which is intended to be air-tight. The spark takes place between steel points, one of which is integral with the steel housing.

The Speco device consists of a spark gap, the electrodes of which are of nickel alloy, which is open to the air. It is surrounded, however, by a Davy copper gauze to prevent the spark from igniting any gasoline vapor which may be present.

The Walden Worcester series gap is made integral with the spark plug of the same name. The electrodes are of nickel alloy and one of them is the central wire of the spark plug, the outer end of which is flush with the surface of the porcelain insulation. The gap is open to the air.

The French, in their aviation engines, have used a form of the series gap called by them the "Carbolyseur." It consists of a gap, at the central point of the distributor, the length of which can be varied at will by the pilot in order to secure the best running of his engine. No detailed description of the "Carbolyseur" is available at the present writing.

Several systems of ignition involving high frequency electrical oscillations have been devised. The Lodge system is the best known of these systems and will be described briefly. It consists simply of one or two condensers which are charged by the magneto or coil, and which discharge across a subsidiary gap, called by the inventor the "primary gap." The spark plug is included in the discharge circuit of the condensers and a spark takes place between the electrodes. The circumstances governing the passage of the spark are identical with those described later in the discussion of the action of the series gap.

Many advantages have been claimed for the series gap and some objections have been urged against it. The former are more numerous than the latter and some of them are so extreme in character that it was considered worth while to tabulate all of the claimed advantages and objections that have come to the attention of the bureau.

(*a*) Advantages claimed:

1. Ability to fire any plug no matter how badly damaged.
2. Increased power, speed, and economy.
3. Fatter, hotter spark.
4. Negligible energy lost in series gap.
5. Increases speed of propagation of explosion.
6. Visible spark gives means of finding trouble.
7. Leaner mixture may be used.
8. Reduces "amperage"; no burning out of breaker points.
9. Increased energy available for ignition.

(*b*) Objections urged:

1. Hard on insulation of ignition system.
2. Causes large drain of current.
3. Causes difficulty in starting.

The experimental and other evidence on the questions above enumerated will now be discussed.

(*a*) ADVANTAGES CLAIMED.

(1) Claim No. 1 is obviously not true. It is, of course, unquestioned that plugs can sometimes be fired by means of a series gap when they can not be fired without it, but the ability of the series gap to fire a fouled or otherwise damaged plug depends entirely upon the value of the resistance shunting the plug gap. If this shunting resistance reaches a sufficiently low value it may become impossible to fire the plug. For the average spark plug and magneto this limiting value of resistance is of the order of magnitude of several thousand ohms. Fouling with a resistance of this order of magnitude is of not infrequent occurrence.

(2) The use of a series gap may result in increased power, speed, and economy, as claimed, but, as far as our present knowledge goes, only indirectly. The increase in magnitude of the quantities named results solely from the fact that the use of the series gap may cause to be fired charges of the explosive mixture which otherwise would be discharged from the engine unignited. The claim of increased power, speed and economy as frequently made is that the use of the series gap will bring about the result mentioned even though every charge was being fired by the engine without the use of the gap. This claim has been investigated experimentally at the Bureau of Standards and found to be unjustified. Experiments were made on both a truck and an aviation engine in which a commercial form of the series gap was attached to each plug. A switch at each plug was provided, whereby the series gap could be short circuited at will. It was found that the running of the engine, and the consumption of gasoline, was entirely unaffected by the presence or absence of the series gaps through the wide range of mixtures, loads, and spark advance used. Experiments to determine whether the character of the spark discharge in the engine cylinder affected the running of the engine were also made. A condenser was connected through a switch to the terminals of a spark plug on one of the cylinders of an automobile engine. The condenser could be connected to or disconnected from the plug at will, thus modifying the character of the spark discharge in the engine cylinder markedly. No difference in the running of the engine could be detected whether the condenser was disconnected from the plug or connected to it. Additional experiments on this point, the results of which have come to the attention of this bureau, justify the conclusion that the character of the igniting discharge has no effect whatever on the running of the engine so long as the spark ignites the explosive mixture.

(3) The claim that the use of a series gap results in a "fatter," hotter spark is of minor importance, as it has by no means been shown that increasing the "fatness" of a spark increases its igniting power. Some experiments were made at this bureau with a plug artificially fouled and a series gap, which showed that whenever the spark passed its appearance was the same, whether there was a series gap present or not, or whether the plug was clean or fouled. The temperature of the spark is a very indefinite thing and little can now be asserted as to the magnitude of that quantity. The heat generated by the passage of the spark, however, can easily be measured. Investigations at the Bureau of Standards have shown that this last-mentioned quantity is in general reduced by the presence of the series gap. Whether or not this reduction in the total energy content of the spark involves a decrease in the igniting power of the spark is not now known.

(4) The ratio of the amounts of energy spent in the plug gap and series gap is equal to the ratio of the sustaining voltages of the respective gaps. The sustaining voltage of the series gap is of the same order of magnitude as that of the plug gap. Consequently the amount of energy lost in the series gap is not negligible.

(5) The experimental evidence obtained up to the present time shows that the character of the spark has no effect on the speed of propagation of the explosion. As mentioned above, experiments on an engine showed that the presence of neither the series gap nor a condenser

made the least difference in the power developed or speed attained. Consequently the effect, if any, of the presence of the series gap upon the speed of propagation of the explosion is too small to affect the power developed.

(6) It has been asserted by the proponents of the series gap that this device is in effect a "window in the cylinder" and that the passage of a spark in the series gap indicates infallibly the passage of a spark between the electrodes of the plug. This is not the case. Not infrequently plugs are so badly fouled that the breakdown of the series gap fails to fire them. Moreover, the passage of a spark across the series gap does not indicate thereby a healthy condition of the ignition system unless the series gap is set for a breakdown voltage equal to or greater than that of the plug.

(7) The use of a leaner mixture when the series gap is employed is due not to the series gap itself but to the fact that upon installing such devices a readjustment of the carburetor is generally made. Many owners of motor cars run with too rich a mixture, and a readjustment of the carburetor in accordance with the instructions of the manufacturer of the series gap results in a leaner mixture.

(8) Readings taken with a direct-current ammeter in series with a clean plug have shown that the presence of a series gap reduces the current as indicated by the instrument. The oscillograph, however, shows that the presence of the series gap has no effect other than to decrease the duration of the discharge between the electrodes of the plug. This is due to the higher sustaining voltage of the combination of plug and series gaps which causes the current in them to stop sooner than it otherwise would. The presence of the series gap does not affect the value of the current while it is flowing. Consequently it is readily seen that the indication of a direct-current ammeter in the circuit will be decreased by the presence of a series gap. This fact is probably the basis for the claim that the series gap reduces the "amperage."

Concerning the effect of the presence of series gaps upon the life of the breaker points little can now be said. The value of the current flowing through the breaker before the points open is probably in most cases not affected by the presence of the series gap. When it is affected, the effect is to increase the value of this current. This is due to the fact, mentioned in the previous paragraph, that when the series gap is used the current in the secondary of the magneto or coil dies out more rapidly than when no series gap is present. Consequently there is less chance of interference between the last part of one discharge and the beginning of the next, with a resulting decrease in the value of the primary current when the breaker opens. The previous sentence is applicable only to the magneto. In the case of the coil operated from a battery, interference rarely if ever takes place.

The above discussion applies to the case of a gap in series with a clean plug. If the gap is in series with a fouled plug, the comparison has to be made between the action of the fouled plug alone and the fouled plug in conjunction with the series gap. Oscillograms have been taken which show that the current in the primary at break, if no series gap is present, is in general the same whether the plug is clean or fouled. If there is any difference between the two cases it is that the primary current is greater when the plug is fouled. It was seen in the preceding paragraphs that the addition of a series gap increases the voltage across the breaker points, and may sometimes increase the primary current at break. Consequently it would be expected that there would be a decrease in the life of the breaker points upon the addition of a series gap in circuit with a fouled plug. Experimental evidence on this point, however, is lacking at present.

(9) The use of a series gap may increase the amount of energy available for ignition only in the sense that it may cause a spark to pass between the electrodes of a plug when without it the spark would not pass. If the spark is going to pass at all, it will pass in such a short time after the opening of the breaker that a negligible amount of energy is lost in that time in the fouling. During the passage of the spark its resistance is small compared with that of the fouling, and consequently the fouling has little effect on the further course of the discharge. If the spark does not pass, the energy that would otherwise be expended in the spark is dissipated in the fouling.

(*b*) OBJECTIONS AGAINST THE USE OF SERIES GAPS.

(1) The series gap in an ignition system can not be set for a breakdown voltage less than that of the plug if the device is to be of any use. Consequently, the breakdown voltage of the combination of series and plug gaps will, in general, be greater than that of the plug gap alone. This state of affairs is not considered to be necessarily detrimental, as the insulation of the magneto or coil is supposed to be able to stand, for long periods of time, a potential equal to the breakdown potential of the safety gap. There is a possibility however, that the continued application of this higher potential may, in the end, weaken the insulation. Experimental evidence on this point is lacking at the present time.

(2) Experimental evidence on the claim that the use of a series gap causes a large "drain of current" has already been presented under section (*a*) 8 above. It was shown there that the series gap has but little effect on the currents in the various circuits.

(3) There is some evidence to show that the presence in an ignition system of a series gap, at least one of fixed length, may cause difficulty in starting the engine. A case was reported to this bureau in which a series gap of variable length was used on a truck engine. After the engine had run for a minute or so, it would continue to run satisfactorily over a wide range of settings of the series gap, from zero up to a maximum length; but, in starting, the series gap had to be entirely closed in order to get the engine to fire. In this case the plugs could not have been very dirty.

In experiments carried out at this bureau on a similar engine with artificially fouled plugs, it was found that the series gap had to be opened wide in order to start but had to be closed somewhat afterwards in order to fire steadily. The interpretation of the phenomena just described is not certain; but there can be no doubt that, in some cases, the presence of a series gap in the circuit is detrimental in starting. The conclusion is that series gaps should be made so that their length can be adjusted easily at any time during the running of the engine.

(B) OUR PRESENT KNOWLEDGE OF THE ACTION OF SERIES GAPS.

SIMPLE THEORY OF THE ACTION OF THE SERIES GAP, AND RESULTS OF EXPERIMENTS MADE TO TEST THE THEORY.

NOTE.—Reference may be made to Report No. 58, Part I, for a more detailed discussion of the cycle of operations of a magneto or coil.

The outline of what takes place during the cycle of operations of a magneto or coil can be given in a few words and will be summarized in the following paragraphs.

The first of the periods into which the cycle of operations can be divided is that just before the opening of the breaker when the current in the primary is increasing due to the action of the electromotive force of the battery in the case of a coil, or that due to rotation in the case of a magneto.

The second of the periods is that in which the voltage builds up after the opening of the breaker. Before the breaker opens current is flowing in the coil. When the breaker opens the circuit this current decreases rapidly, in so doing charging the condenser and inducing an E. M. F. in the secondary. If the gap did not break down, this would go on until all the energy was electrostatic in form; but in general the gap breaks down before this stage is reached. Any arcing at the break lessens the rate of change of current, and so lessens the maximum voltage attained during this period.

When the discharge first begins to flow between the electrodes in the plug, it probably consists of a condenser discharge; that is, the capacity of the high tension winding discharges through the plug gap and the course of the discharge is much too fast for the ordinary oscillograph to record. This state, however, lasts only for a very short time, and then the discharge becomes a steady arc with approximately constant sustaining voltage. The effect of capacity in parallel with the plug, in particular the capacity of the leads and any apparatus connected to them, is to decrease the rate of rise of the E. M. F. and also the maximum value attained by it. If there are any dielectric losses in the insulating materials of the system, the same effect, that is, decreased rate of rise of the E. M. F. and smaller value of maximum voltage, will be produced.

The phenomenon described in the preceding paragraph applies to the case where the insulation resistance of the plug is high. If the plug is fouled, the insulation resistance is greatly decreased and the cycle of operations is somewhat different. The effect of this resistance shunting the plug gap is to decrease the value of the maximum voltage by diverting to the fouling energy which would otherwise go to charging the capacity in parallel with the plug. Another way of interpreting the phenomenon is that the fouling diverts to itself current that would otherwise charge the capacity in parallel with the plug and increase the voltage. The potential difference across the plug at any time must necessarily equal the ohmic drop in the fouling and can not be less than the breakdown voltage of the plug if the plug is to fire the charge. The problem then is to increase by suitable means the ohmic drop of the fouling.

The simplest means to secure the increased ohmic drop in the fouling is to insert an additional gap in the high tension circuit. If this be done, the equivalent simple circuits are as shown in figure 1. The plug gap and the series gap are labeled as such in the figure. R represents both the fouling and its resistance, while the three condensers shown in the figure

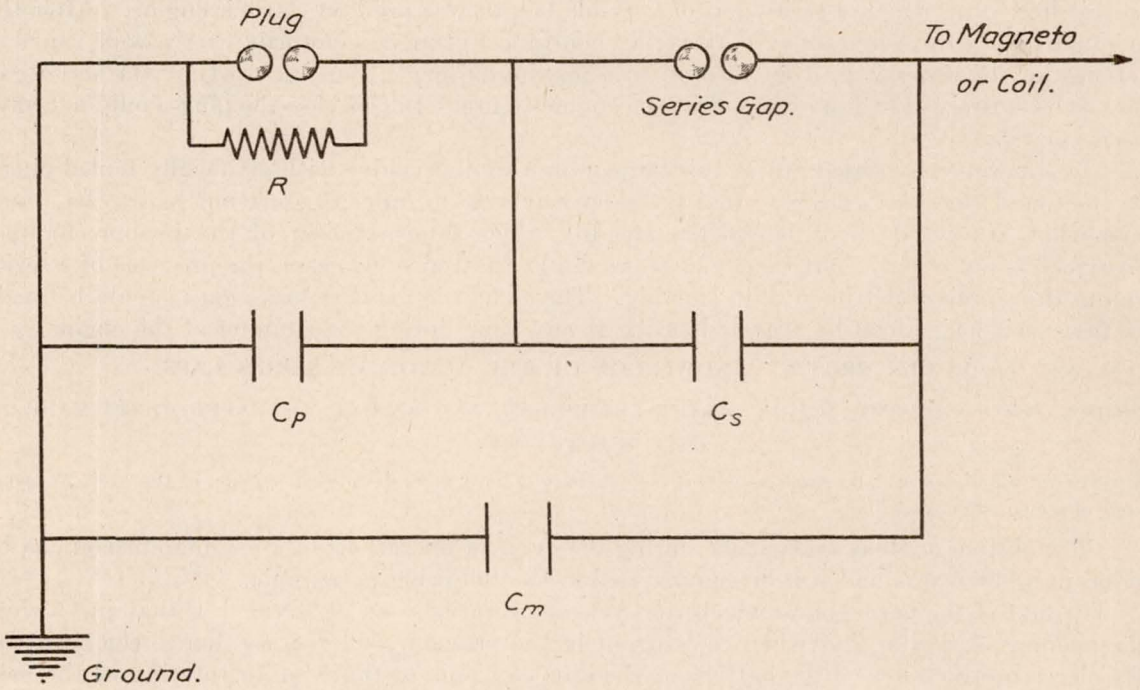


FIG. 1.

represent the distribution of capacity between the different parts of the apparatus. Let E_p and E_s represent the breakdown potentials of plug and series gaps, respectively, and e_m the voltage furnished by magneto or coil at time t. The mode of operation of the apparatus, neglecting the self-induction of the circuits and various other circumstances which need not be mentioned in detail here, is as follows:

The voltage furnished by magneto or coil, e_m increases after the opening of the breaker. During the increase, C_m is charged to potential e_m, as is likewise C_s, if R is small, say not greater than 100,000 ohms. When e_m reaches E_s, the series gap breaks down and a current flows to charge C_p. C_s discharges at the same time but this discharge has only a slight effect.

The potential to which C_p is raised by the discharge just mentioned is approximately

$$e_p = \frac{C_m \times E_s}{C_m + C_p} \tag{1}$$

If e_p is less than E_p, the plug can not fire. In any event a finite interval of time must elapse before the plug gap can break down during which time the potential of C_p is decreasing due to current flowing in R. If R is small, the plug gap may not break down at all, even though

e_p is greater than E_p. The effect of varying the different constants of the circuit is easily seen as follows:

A decrease in R obviously decreases the ability of the system to fire the plug due to the increased amount of charge which flows through the resistance and decreases the potential of C_p. To offset such an effect an increase in e_p is required. As can be readily seen by reference to equation (1), this can be brought about by an increase in C_m or E_s, or both. An increase in R causes the reverse effect. If R is large (of the order of 100 megohms) the condenser C_p is virtually insulated instead of being short circuited by R. Under these conditions, the voltage across C_p and C_s, before any spark passes, are respectively

$$\frac{C_s}{C_s+C_p}\, e_m = e_p \tag{2}$$

and

$$\frac{C_p}{C_s+C_p}\, e_m = e_s \tag{3}$$

Each of these voltages is smaller than e_m. Consequently, if a plug is clean, the applied voltage e_m required to spark the combination of plug and series gaps may be larger than if the plug is fouled, provided the resistance of the fouling is not too low.

It is seen from equation (1) that an increase in C_p causes a decrease in e_p; consequently, it is in general advantageous to keep the capacity in parallel with the plug as small as possible. The one exception to this statement is for the case when the plug is clean. Under these conditions, it is seen from expression (3) that the voltage across the series gap increases with C_p, and therefore that the series gap will discharge more easily, the larger is C_p. An increase in C_p, however, makes the plug gap harder to fire, consequently C_p can not be increased beyond a certain limit without causing the plug to stop firing.

The capacity in parallel with the series gap has little effect on the operation of the system. During the discharge the presence of this capacity increases the current through the series gap. This increase in current causes an increase in the ionization in the series gap and consequently a slight decrease in the resistance of the series gap. If the plug is fouled, the capacity C_s is in parallel with C_m when the condensers are being charged and hence decreases slightly the maximum voltage furnished by the magneto or coil.

The effect of increasing C_m is seen from equation (1) to increase the voltage applied to the plug when the series gap breaks down. Consequently from this standpoint a large value of C_m is beneficial. However, increasing C_m decreases the maximum value of the potential furnished by the magneto, and so if C_m is increased too much the magneto will no longer be able to spark the plug gap.

Various experiments, made to test the above outlined theory of the action of the series gap, have come to the attention of this bureau. Some were made on plugs fouled by use in an engine and some on clean plugs shunted by a water resistance. Other experiments, instead of being carried out on a spark plug, were carried out on a gap consisting of a wire going through a hole in a plate. In all three cases, the subsidiary gap was a ball gap. The value of the shunting resistance in the last case was 10,000 ohms. The results of the experiments confirm the main features of the theory; that is, the change in the sparking ability of the system due to changes in the capacity and resistance of the various parts follows the requirements of the theory, with the exception of some anomalies which were ascribed to the oscillatory character of the discharge of the series gap. Evidence was also found that the actual fouling has a much lower resistance at high voltages than it has at low voltages, as though the conduction at high potentials were in the nature of arcs passing from particle to particle of the fouling. One of the most important conclusions reached was that the length of the series gap necessary to fire a fouled plug is extremely variable, and consequently any series gap used on an engine should be capable of easy adjustment while the engine is running.

The experimental evidence obtained at the Bureau of Standards, which need not be given in detail here, also confirms all the main features of the theory. One point worthy of note is that it was found possible to fire a plug in an engine when the resistance of the fouling, as measured by a megger, was as low as 4,000 ohms.

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DIFFERENCE BETWEEN THEORY AND ACTUAL CONDITIONS IN THE OPERATION OF SERIES GAPS.

In discussions of the action of the series gap many conditions are frequently postulated for simplicity, either directly or by implication, which do not correspond to actual facts. These points of difference between the simple theory and actual conditions will be treated in detail in the following paragraphs as they must be considered in dealing with the question of series gaps.

The first point for discussion is the question of the potential given by a magneto or coil. It is generally asserted that this potential is seldom or never the same from one cycle of operations to the next. This statement has frequently come to the attention of this bureau. A justification given for this statement is that when a magneto or coil is sparking a gap, the maximum voltage as read by a crest voltmeter (a static voltmeter in series with a kenotron) is always varying; and also that at certain times the system is able to spark a longer gap than it is at others. These facts, however, could be just as well, or rather better, accounted for by a variation in the breakdown voltage of the gap instead of in the potential furnished by the magneto or coil. Experiments to test this point were made at the Bureau of Standards.

A magneto driven by belt from a motor was connected directly to a crest voltmeter, no spark gap except the safety spark gap of the magneto being in the circuit. At first it was run at approximately 300 revolutions per minute, the speed of the magneto at any instant being rather variable. The safety gap did not discharge at all. The voltage as read by the crest voltmeter was constant to within 1 per cent. The speed was then increased. As a consequence it was necessary to connect a condenser to the terminals of the magneto in order to prevent the safety gap from discharging. The voltage was even more constant than at the lower speeds; and, in fact, up to the highest speed employed in the experiment (1,600 revolutions per minute) the higher the speed the more constant the reading of the crest voltmeter. Conditions at speeds greater than 300 revolutions per minute, where a condenser had to be connected to the terminals of the magneto, are not quite comparable with conditions existing when the magneto is firing a gap; but at 300 revolutions per minute where no condenser was used they are directly comparable with the conditions of actual use. The experiment was tried of measuring the voltage with a crest voltmeter when the magneto was firing a gap at 300 revolutions per minute. The reading of the voltmeter was extremely variable. These facts show conclusively that any variation in the power of a magneto to spark a gap is due to variability in the gap rather than in the magneto.

The next point to be considered is the variability of sparking potential of the series gap due to one or more of the causes now to be discussed. It is a well-established fact that any change in the surface of the electrodes of a spark gap in general changes the sparking potential. In particular the long-continued passage of a discharge corrodes the surface, furnishing numerous points from which the discharge can pass, and increases the distance between the electrodes. These two varieties of change in surface conditions have opposite effects. The roughening of the surface makes the spark pass at a smaller value of the potential, and the increase in distance makes the spark pass at a higher potential. The total effect is probably first a slight decrease and then an increase in the sparking potential.

The temperature of the electrodes also has an effect on the breakdown voltage. If the electrodes are hot, the temperature of the gas between the electrodes is increased, and consequently the breakdown voltage of the gap is decreased if the gap is in communication with the atmosphere. If the gap is hermetically sealed, a variation in the temperature of the gas has no effect on the breakdown voltage. A further effect of an increase in the temperature of the electrodes is to change the nature of the surface films upon them. In general, an increase in temperature tends to dissipate the surface films, which have such a marked effect, usually inhibitory, on the passage of a discharge between the electrodes.

The medium in which the electrodes of the series gap are immersed is subject in general to changes in nature, pressure, and temperature. The only case in which a change in nature is to be expected is when the gap is tightly inclosed. Under these conditions the passage of a discharge causes chemical changes in the air, which have some effect, probably small, on the breakdown voltage. The changes in breakdown voltage due to changes in temperature and

pressure obey well-known laws, namely, the breakdown voltage is approximately proportional to the density and is only affected by temperature and pressure as they affect density.

The breakdown voltage of a series gap may be affected by the "hardness" of the gap. A gap is said to be hard when it has a higher breakdown voltage for rapidly varying potentials than it has for slowly varying potentials. Hardness is of two kinds. If the electrodes are pointed, the gap is hard, due to its own form. For a rapidly varying potential, that is, one that rises quickly to a maximum and then decreases to approximately zero in a very short time (in other words, such a wave of potential as a magneto gives), the potential across a gap with pointed electrodes frequently rises to as much as twice or three times the normal breakdown voltage without a spark passing. Obviously, then, pointed electrodes are not suitable for use either for plug or series gaps.

For electrodes that are not pointed, that is, ones not having a radius of curvature small compared with their distance apart, hardness of the kind above described does not exist. Electrodes of this kind may be subject to a hardness due to some condition of the surface such that the breakdown voltage for a rapidly varying potential is somewhat larger than that for a slowly varying potential but rarely more than 1.5 times as great. The condition of the surface which produces such hardness is not well understood. It is known, however, that films of oil are capable of producing it. Consequently, in designing gaps, allowance has to be made for times when the breakdown voltage is abnormally large.

The effects of previous discharges across a gap are to modify the hardness, as described in the immediately preceding paragraph, and to cause a greater number of ions than normal to be present in the gap. The hardness of the gap is as likely to be increased as it is to be decreased. The presence of an abnormally large number of ions in the gap has no effect upon the breakdown voltage of the gap but does cause the discharge to pass more promptly than it otherwise would.

Change in dimensions due to temperature changes may occur in the series gap. The principal danger is not due to isotropic expansion but to warping owing to a strained condition of the structure of the gap.

Series gaps have not been used extensively enough to permit the accumulation of any data as to the importance in practice, relative or absolute, of the different effects named above.

The plug gap is affected by all the conditions that have just been enumerated. The different circumstances in the engine cylinder, however, modify the relative importance of these conditions.

The plug gap is subject to much more corrosion than is the series gap on account of the much higher temperatures prevailing in the engine cylinder, which are so high that surface films are probably prevented from forming.

Variation in the proportions of the mixture probably has little effect on the breakdown voltage. Variation in the compression has considerable effect, the breakdown voltage being proportional to the density of the charge at the moment of firing.

The presence of oil in the gap generally increases the breakdown voltage because the discharge is obliged to follow a much longer path through the gas than if the oil were not present. It is possible, if there is not much oil in the gap, that the breakdown voltage may be decreased because it is well known that sparks will pass over considerably greater distances along the surface of insulators than they will directly through the gaps. It is generally thought, however, that this condition is seldom realized. The presence of carbon on the electrodes decreases the breakdown voltage. Not infrequently the carbon forms a bridge from one electrode to the other and effectually short circuits the plug.

The higher temperatures prevailing in the engine cylinder render any change in the dimensions of the gap, due to temperature, more important than is the case in the series gap; but with a proper design of plug, this effect is not to be feared.

In view of the high temperatures existing in the engine cylinder, it is thought that plug gaps never exhibit the phenomenom of hardness. This opinion is particularly important for the problem of the series gap because when the series gap breaks down the voltage on the plug gap increases at a rate thousands or millions of times greater than the rate at which potential

is applied to the series gap. Any hardness found in the plug gap will probably cause much greater variations in the breakdown voltage of the plug than will the same amount of hardness in the breakdown voltage of the series gap.

A further point of difference between the simple theory of the action of the series gap and actual conditions with a fouled plug is found in the fact that the resistance of the fouling decreases as the E. M. F. applied to it increases. The evidence on this point has been already given. It is easily seen that this characteristic of the fouling requires a larger increase in the breakdown voltage of the series gap for a given increase in breakdown voltage of the spark plug gap than if the resistance of the fouling were constant.

It was seen that an improvement in the action of the series gap could be secured by putting a condenser of suitable capacity in parallel with the source of E. M. F. This condenser should have as small dielectric losses as possible, as the maximum E. M. F. of the magneto or coil is decreased by an amount which depends directly upon the magnitude of the losses.

In discussions concerning the action of the series gap, it is practically always assumed that the passage of a discharge between the terminals of the plug will always fire the charge, and consequently, that the problem is solved when the plug can be made to pass a spark at the proper time in every cycle of the engine. That this assumption is not always true, is shown by the circumstances reported to this bureau and mentioned above, that a certain engine would not start with the series gap in circuit but would run with the gap in circuit after being started. Some experiments at the Bureau of Standards made, it is true, with a smaller gap than is usual in plugs (0.15 to 0.30 mm.) gave the following results: A gap was inserted in series with a clean plug in one of the cylinders of a four-cylinder engine. When the length of the series gap was zero the cylinder would miss steadily. As the length of the series gap increased the missing became less, and at a certain value of the gap the engine fired perfectly. As the length of the series gap was still further increased, the cylinder fired perfectly for a short range. As the gap was increased still further, however, missing began again, and for a still further increase in length the cylinder missed all the time. At all times during the experiment the series gap would pass a discharge at the proper instant of each cycle. When the cylinder was firing perfectly, obviously a discharge must have been passing between the electrodes of the plug. When the length of the series gap was increased and a discharge still kept passing in it, the plug in the engine cylinder must have given a spark for each discharge of the series gap. This fact shows that a spark between the terminals of a plug does not necessarily fire the charge in the engine cylinder, even though there is no change in the composition or density of the charge. It is not known whether any phenomena similar to those just described take place for spark-plug gaps of the dimensions generally used (0.50 mm.), but it will be well in any discussion of the action of series gaps to bear in mind the possibility of their occurrence.

(C) THE DESIGN OF THE SERIES GAP.—FORM AND MATERIALS OF ELECTRODES.

GENERAL DESIGN.

The following requirements must be satisfied by a series gap if it is to be of practical use. Its breakdown voltage must be reasonably constant and greater than that of the plug; it must be able to spark the plug for the lowest value of fouling resistance likely to be met with in practice; and it must be reliable in action and of reasonably long life. In the following paragraphs will be pointed out the way in which the above requirements affect the design of the gap.

FORM AND MATERIAL OF ELECTRODES.

The first question to be decided is that of the form and material of the electrodes, as these are by far the most important factors in determining the breakdown voltage of the gap. In this connection it has been suggested that a multiple gap could be used instead of a single gap. There is at present practically no evidence that a multiple gap would offer any advantages over a single gap. As to the shape of the electrodes, it was seen above that pointed electrodes are entirely unsuited for use either in the series gap or in the plug gap, and that in order to avoid hardness the radius of curvature of the electrodes should not be small compared with the dis-

tance between electrodes. As long as this condition is satisfied the precise shape of the electrodes seems to make no difference.

The requirements that the material of the electrodes should satisfy are as follows: The breakdown voltage should be constant; the material should have good mechanical properties, high thermal conductivity to prevent heating, and should corrode but little in order that the gap should have a long life. Nickel alloy wire of the sort used in spark plugs would seem to satisfy these requirements best at the present time.

INSULATION OF GAP.

The insulating material supporting the electrodes of the series gap should have, first and foremost, a very high insulation resistance. This is absolutely necessary because any leakage between the electrodes of the gap is fatal to the gap's functioning. This material should be able to stand heat without impairing its insulating properties, if the gap is integral with the plug; and if the gap is tightly inclosed should be able to withstand corrosion by the nitric acid which is formed from the air by the passage of the spark.

HOUSING OF THE GAP.

The series gap may be either in communication, more or less direct, with the atmosphere, or may be tightly inclosed, even hermetically sealed. If the gap is open to the atmosphere, there is little opportunity for corrosion by the discharge, and the consequent probable impairment of the insulating properties of the housing. However, there is a certain fire risk if any considerable amount of gasoline vapor should be in the vicinity of the gap. Tests at the Bureau of Standards have shown that this fire risk may be eliminated by the use of a Davy gauze inclosing the gap. A further point to be considered in connection with a gap open to the atmosphere, when used on an aviation engine, is that at high altitudes the breakdown potential of the gap is decreased. However, the density of the charge in the engine cylinder is correspondingly decreased, and the result is to preserve unchanged the ratio of the breakdown voltage of the series gap to that of the plug gap. If the gap is hermetically sealed, the products of discharge can not escape, and there is a chance that the insulation resistance of the housing may be decreased. Nothing is known at present about the amount of the products of discharge and their effect upon the insulation resistance of the housing. A tightly inclosed gap gives rise to no fire risk and has a constant breakdown voltage irrespective of altitude. As the breakdown voltage of the plug in the engine cylinder decreases with increase in altitude, it is seen that a tightly inclosed gap offers great advantages in the matter of firing fouled plugs at high altitudes. The adjustment of the length of a tightly inclosed gap, however, demands some attention. The present state of our knowledge of the subject points to the necessity of the pilot being able to adjust conveniently and at any time the length of the series gap. To satisfy this requirement in a tightly inclosed gap is not impossible, but evidently complicates the design and manufacture of the gap considerably.

LOCATION OF THE GAP.

The series gap has been placed in several locations: Integral with the plug; at the plug, but not integral with it; and at the center of the distributor. These various positions have their advantages and disadvantages. If the gap is integral with the plug, it is in the best position electrically, because the capacity of the leads is directly in parallel with the magneto. However, if the gap is integral with the plug, it can not be adjusted while the engine is running without the addition of an undesirable amount of mechanism. Also the series gap in this place will get hot, and its breakdown voltage will be subject to considerable variations. If the gap is at the plug but not integral with it, it is still in the best place electrically, will not get so hot, and will not be so subject to variations in its breakdown voltage. It can not be adjusted, however, while the engine is running without additional mechanism. If the gap is at the distributor, it is not in such a good place electrically for firing a fouled plug. The capacity of the leads to the plug is in this case directly in parallel with the plug and consequently has a detrimental

effect on the ability of the series gap to fire the plug. There is only one case in which this position of the capacity may be advantageous. It was previously shown that for a clean plug it is partially advantageous to have the capacity in parallel with the plug. A further advantage of having the gap at the distributor is that its length can be adjusted easily while the engine is running. As was seen from the data given above, a gap of fixed length does not seem to be at all suited for the function of firing a fouled plug, and consequently, in order to be of any considerable amount of use, the gap should be capable of adjustment while the engine is running. It is possible, however, that one adjustable gap at the center of the distributor which serves all the plugs may not be a good arrangement, for some of the plugs may be clean and some may be fouled, the clean plugs requiring a different length of gap for their effective firing than the fouled plugs. This suggests the possibility of having a gap in series with the lead to each plug and close to the distributor. This would call for a separate adjustment of the length of each gap. Whether the additional amount of apparatus thus required and the additional amount of attention required from the pilot (in the case of an airplane engine) would be justified by the results obtained is a matter for practical test.

(D) DEGREE OF UTILITY TO BE EXPECTED OF SERIES GAPS.

As a result of the evidence given above, it may be concluded that the modification of jump-spark ignition systems by the addition of a properly designed and operated gap in series with each plug may remedy effectively a considerable part of the trouble due to cases of fouling met in practice. At present the limits of the method are not known; that is, one can not say definitely just what is the lowest fouling resistance which can be handled by a series gap on a given ignition system and, conversely, whether a given ignition system can or can not, by the use of a suitable series gap, be made to spark a plug with given fouling resistance. The possibilities of the device, however, are well shown by the fact, mentioned before in this report, that it was found possible in one case by using a series gap on an average ignition system (magneto) to spark a plug having the extremely low value of fouling resistance of 4,000 ohms. The only other positive conclusion that can be stated now is that the length of the series gap should be capable of easy adjustment by the operator of the engine at any given time.

In addition to work done in the laboratory and on a few engines, the installation of a large number of gaps in practice and a careful record of their performance is necessary before the question of the practical utility of the series gap can be considered as entirely settled. This practical test can be carried out at any time and independently of laboratory work, and its results would be of the greatest value.

REPORT No. 58

CHARACTERISTICS OF HIGH-TENSION MAGNETOS

Part I.—CYCLE OF OPERATION OF JUMP-SPARK IGNITION SYSTEMS
Part II.—TRANSFORMATION RATIO AND COUPLING IN HIGH-TENSION MAGNETOS

BY

F. B. SILSBEE

Bureau of Standards, Washington, D. C.

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REPORT No. 58.

PART I.

CYCLE OF OPERATION OF JUMP-SPARK IGNITION SYSTEMS.[1]

By F. B. Silsbee.

RÉSUMÉ.

The purpose of this report is to outline briefly the succession of operations which occur in high-tension ignition systems in order to show the connection between the various phenomena concerned and their relative importance on a basis of the energy transformed. It is hoped in ater reports to give in detail the results of measurements of various individual parts of this cycle of operations, and the present report is issued as a basis for interrelating these later discussions.

Throughout the report numerical values are given for the different electrical quantities involved. These values have been obtained by actual measurements of various magnetos recently tested at the Bureau of Standards. They may be considered as typical of this class of apparatus. Figures 4 to 17, inclusive, give reproductions of oscillograms taken on magnetos while operating under various conditions.

The cycle of operation of the jump-spark system can be split up into a number of periods. During each period the electrical phenomena proceed under fairly definite conditions, each period in turn being separated from the one preceding and the one following it by an abrupt change of conditions.

Period No. 1 includes the building up of current in the primary winding as a result of either the impressed voltage from a battery or the voltage generated by the rotation of a magneto armature. The result of this period is the establishment of a current (I_b) in the inductive winding.

Period No. 2 covers the short interval between the instant of the interruption of the primary current by the circuit breaker and the breaking down of the spark gap in the engine cylinder. During this period the magnetic energy of the coil is in part transformed into electrostatic energy and charges the condenser and capacity of the secondary leads.

Period No. 3 is a second very short interval (0.00005 second) beginning at the instant at which the spark gap breaks down and lasting until a steady arc is established in the gap.

Period No. 4 extends from the establishment of the secondary current in a steady arc across the spark gap to the extinction of the spark. Its duration is quite appreciable and may be several thousandths of a second. It is during this period that most of the spark energy is dissipated.

Period No. 5 covers the short interval during which the spark is being extinguished by the closing of the contact breaker.

Period No. 6 covers the remainder of the cycle during which the circuits are practically free from current previous to the beginning of period No. 1 of the following cycle.

The above division into periods applies with slight modifications to both battery and magneto ignition systems. It is believed that a clear recognition of the very different conditions which exist during the various periods will result in a better comprehension of the extremely complicated phenomena which occur in these forms of electrical apparatus.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 20.

INTRODUCTION.

The purpose of this report is to outline briefly the salient features of operation of the high-tension magneto, and of the similar battery ignition systems, and to trace the various transformations of energy which take place. The results of numerous measurements on such systems as have been studied at the Bureau of Standards will be quoted in illustration of these properties. These phenomena are doubtless understood by magneto designers, but with the exception of the excellent papers by Armagnat and Young referred to below, the literature of the subject is very meager and consists chiefly in elementary expositions for the instruction of the amateur automobilist.

The cycle of operations of a jump-spark system can be divided into a number of periods. During each period the electrical phenomena proceed under fairly definite and constant conditions, each period being separated from the one preceding and the one following it by an abrupt change of conditions. It is hoped in later reports to discuss in greater detail and in a more quantitative manner the phenomena of certain of the periods; and the present report is issued as a basis for interrelating these later discussions.

The operation of the usual forms of battery ignition systems is quite similar in many respects to that of the magneto, and the greater part of the following discussion is applicable to both, with suitable changes in the values of the various constants. The principal points of difference in the two types of apparatus are discussed later under "Battery Systems."

Throughout this report frequent reference will be made to numerical values of the various quantities which may be expected in a typical case. For this purpose a magneto having the constants in the following Table I has been chosen. These constants do not precisely fit any individual magneto but are representative of values measured on a number of different types recently tested.

TABLE I.—*Constants of Typical Magneto.*

Primary turns (N_1)	160.
Secondary turns (N_2)	8,000.
Ratio of turns (n)	50 : 1.
Primary resistance (R_1)	0.5 ohm.
Secondary resistance (R_2)	2,500 ohms.
Primary inductance (L_1)	0.015 henry.
Mutual inductance (M)	0.74 henry.
Secondary inductance (L_2)	36 henrys.
Primary condenser (C_1)	0.2 microfarad.
Secondary (distrib.) capacity (C_2)	50 micro-microfarads.
Normal speed of operation	2,000 r. p. m.
Primary current at break (I_b)	4 amperes.
Maximum current in spark	0.075 ampere.
Breakdown voltage of gap	5,000 volts.
Sustaining voltage of gap	600 volts.

OUTLINE OF OPERATION.

The high tension magneto combines in a single machine the functions of an electric generator and of an induction coil, and these two functions are to a considerable extent independent of one another.

The circuits of a high-tension magneto are substantially as shown in figure 1, P being the primary winding which has a few turns of coarse wire and consequently a low resistance, while the secondary winding S has several thousand turns of fine wire. The two coils are wound one over the other on a common iron core, which (in the ordinary or shuttle type) has the form shown in figure 3. Condenser C_1 is connected across the terminals of P primarily to reduce the sparking at the contact breaker B. The electrostatic capacity between the secondary winding or high tension leads and the grounded frame of the machine is sufficiently large to have a material effect on the operation. This capacity is in part distributed along the windings and various portions are consequently subject to different voltages. The effect of this capacity may, however, be approximately represented by an equivalent condenser connected as shown dotted in C_2, figure 1.

The rotation of the armature in the field of the permanent magnets $N S$, figure 3, generates a current in P which flows through contacts B. When a spark is desired, breaker B is suddenly opened by a cam. The current decreases rapidly, producing a high voltage $M \frac{dI}{dt}$ in the secondary. This is led through a distributor (not shown) to the spark gap G in the proper cylinder of the engine. This gap breaks down at usually much less than the maximum available voltage and the magnetic energy originally stored in the primary is transferred to the secondary and dissipated in the gap.

Magnetos may be classified as "two-spark," "four-spark," etc., according to the number of sparks produced per revolution of the rotor. The shuttle core type gives two sparks while most inductor type machines give four. As a rule all the alternations are substantially alike except for the polarity of the induced voltage, though lack of symmetry in a four-spark machine may cause slight differences. Special magnetos designed to fire V-type motors such as the "Liberty 12," where the angle between the blocks is not a simple submultiple of the angle between the cranks, may have successive alternations of materially different wave form. (See figure 4, which shows the primary and secondary currents of such a magneto.) The discussion below, however, will apply to any one alternation in any case.

DETAILS OF OPERATING PERIODS.

The time occupied by one alternation of the magneto may be subdivided into six periods during each of which the circuit conditions are substantially constant, but between which there is a more or less abrupt change in these conditions. These periods are listed in the following table and discussed in more detail below. (See figure 12.)

Period.	Begins.	Ends.	Conditions during period.
1	Max. flux	Breaker opens	Breaker closed, current building.
2	Breaker opens	Gap breaks down	Breaker open, gap open, capacity charging.
3	Gap breaks down	Steady arc established	Breaker open, gap closed, capacity discharging.
4	Arc established	Breaker closes (arc dies out)	Breaker open, gap closed, coil discharging.
5	Breaker closes	Capacity fully discharged	Breaker closed, gap open, capacity discharging.
6	Capacity discharged	Max. flux	Breaker closed, gap open, eddy currents dying out.

PERIOD 1.

During Period 1, the breaker is closed and the armature rotates from the position of maximum flux to the firing position where the cam causes the breaker to open. This period corresponds to about 100° rotation in our typical example and hence lasts 0.008 seconds. During this time the reduction in flux builds up a current (in our example 4 amperes) which tends to maintain the original flux after the rotor has passed the neutral position.

If there were absolutely no resistance in the primary winding or breaker contacts the current would build up to such a value that the armature flux would be maintained constant when rotated to a position at right angles to or even opposing the magnetomotive force of the permanent magnets. This maintenance of the flux is shown quite clearly in figure 20, which shows the total flux through the armature core plotted against angular position (or time) for three different conditions. Here curve I shows the flux through the core on open circuit and is due to the permanent magnets only; curves II and III give the total flux during normal operation of the magneto at low and high speed respectively, and curve IV shows the flux if the primary is left short circuited throughout a complete cycle. The action of the primary circuit in thus closing about the flux produced by the permanent magnets and permitting it to be moved unaltered to a new position is in a sense analogous to the action of an electrophorous in which the charge produced by induction from the exciting charge on the dielectric slab is insulated and moved out of the field of the permanent charge. In either case, the energy is obtained from the motion of the system and the permanent magnets or fixed charge suffer no depletion. The closing of the breaker corresponds to the opening of the ground connection to the electrophorous plate at the beginning of its motion, and the opening of the breaker corresponds to the discharge of the plate after its removal from the slab.

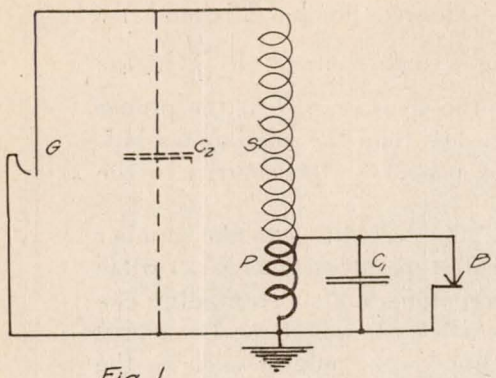


Fig. 1

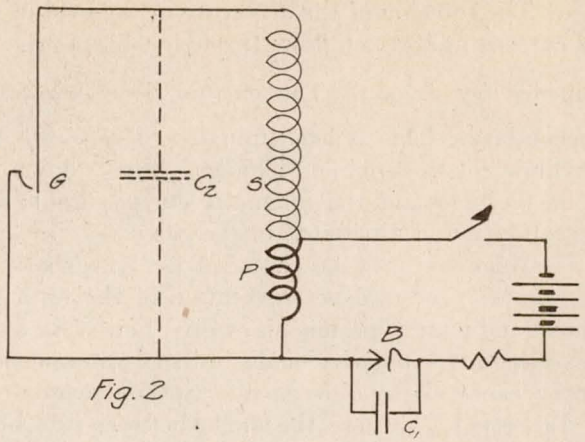
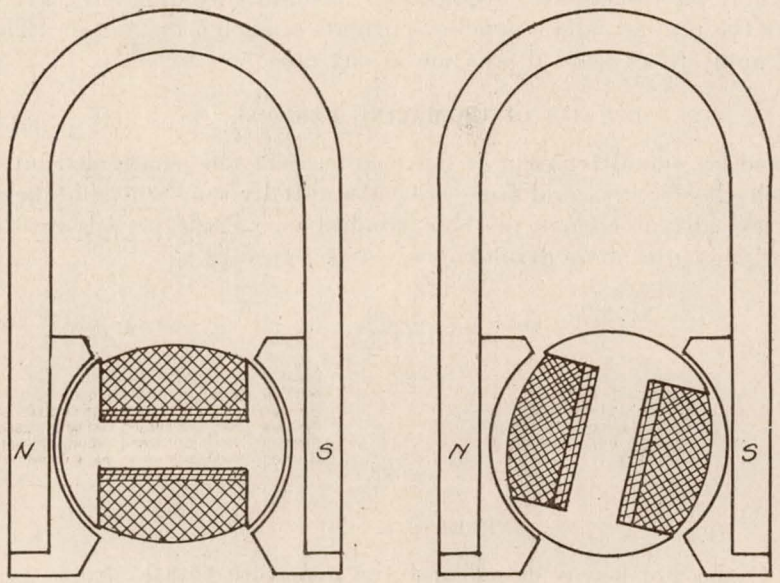


Fig. 2



A Fig. 3 B

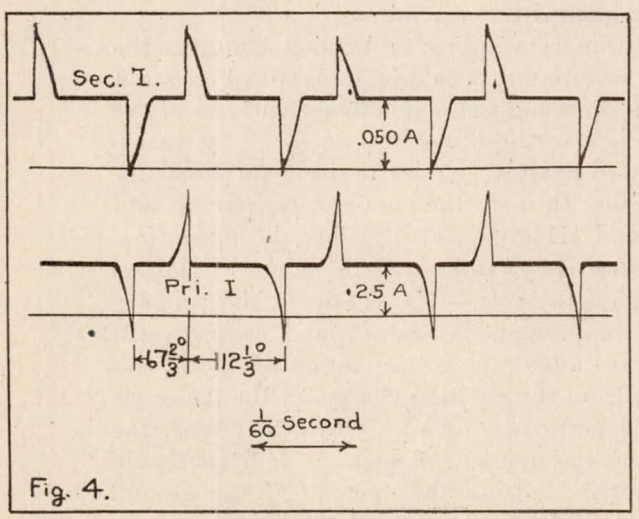


Fig. 4.

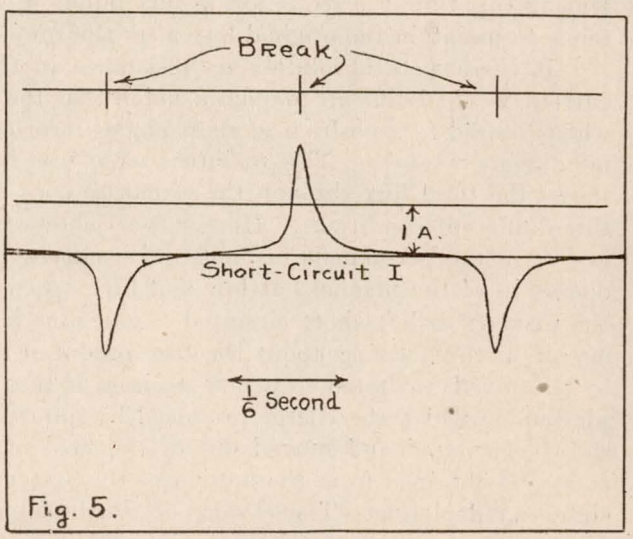


Fig. 5.

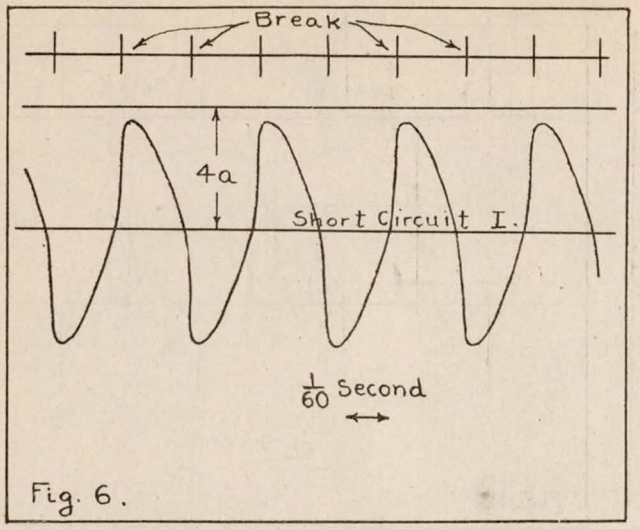


Fig. 6.

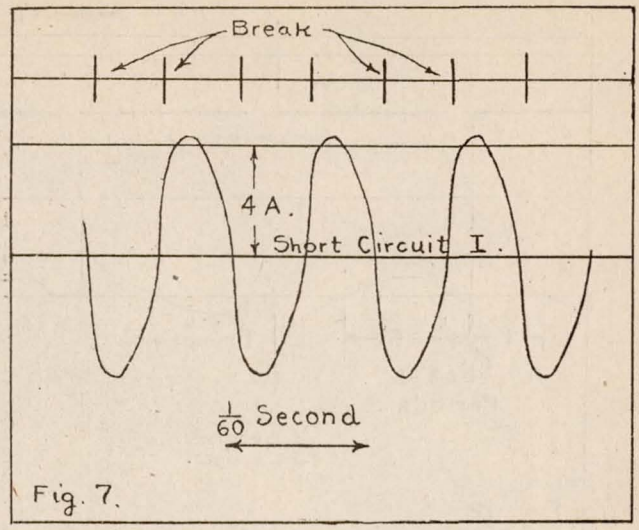


Fig. 7.

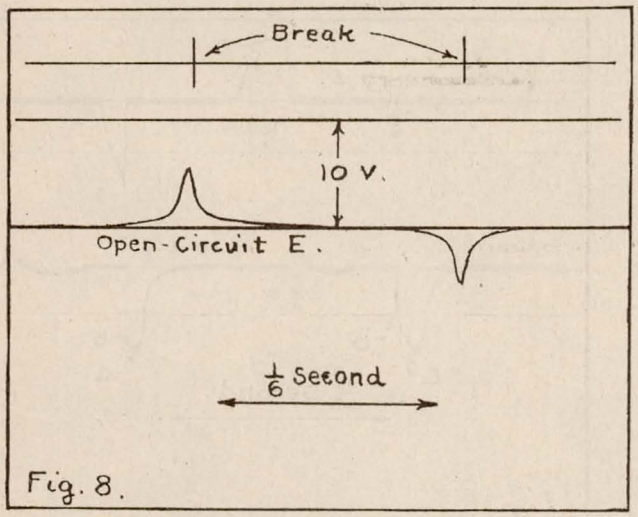


Fig. 8.

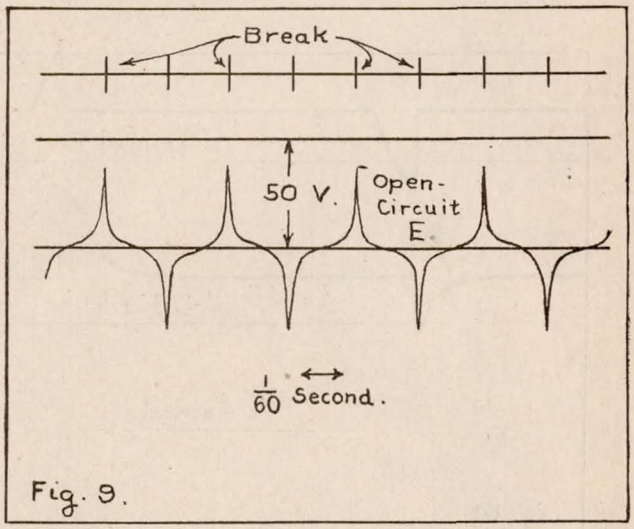


Fig. 9.

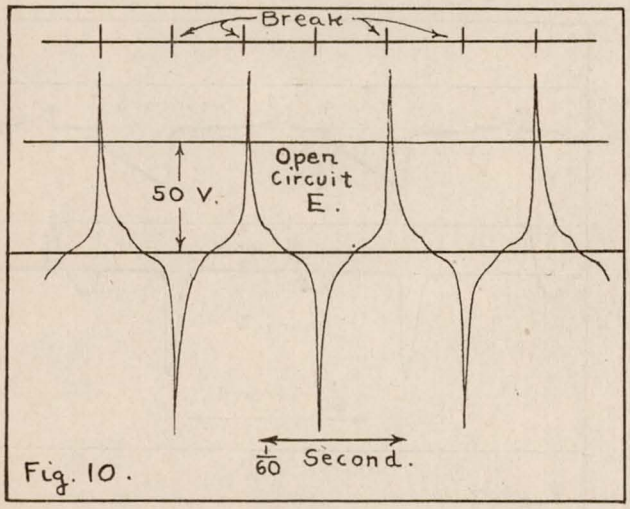


Fig. 10.

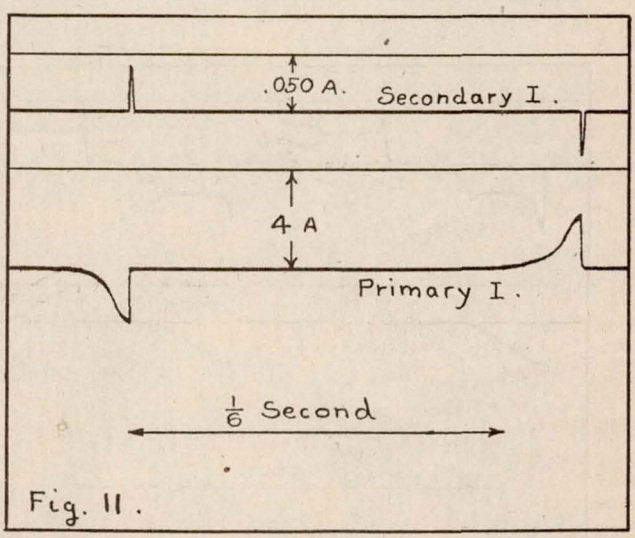


Fig. 11.

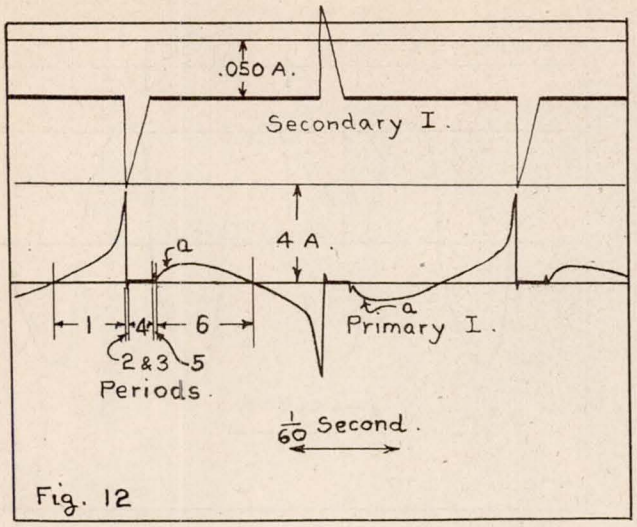


Fig. 12

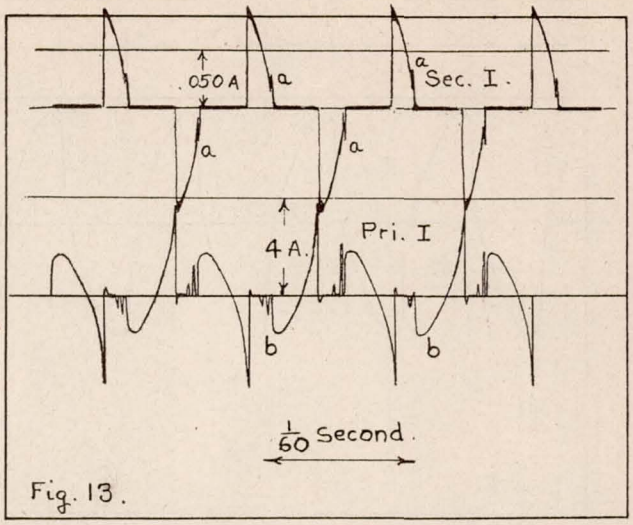


Fig. 13.

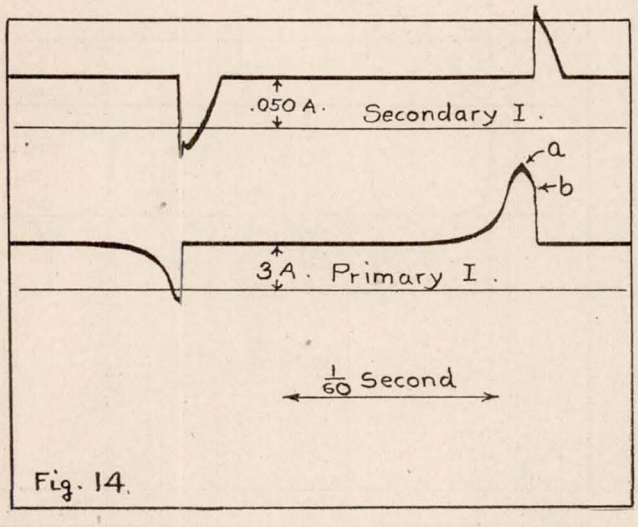


Fig. 14.

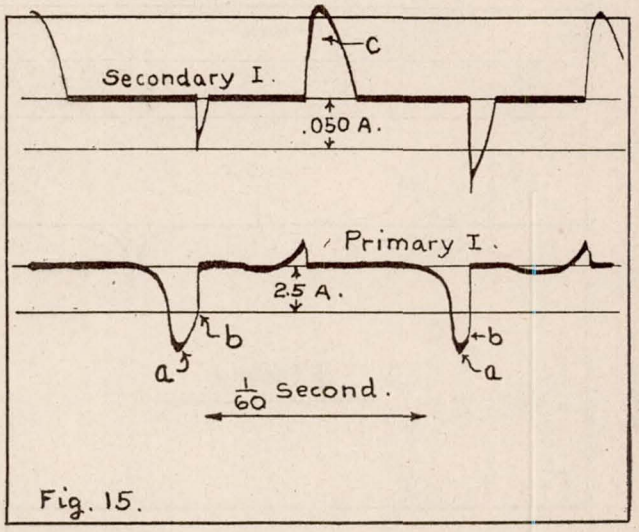


Fig. 15.

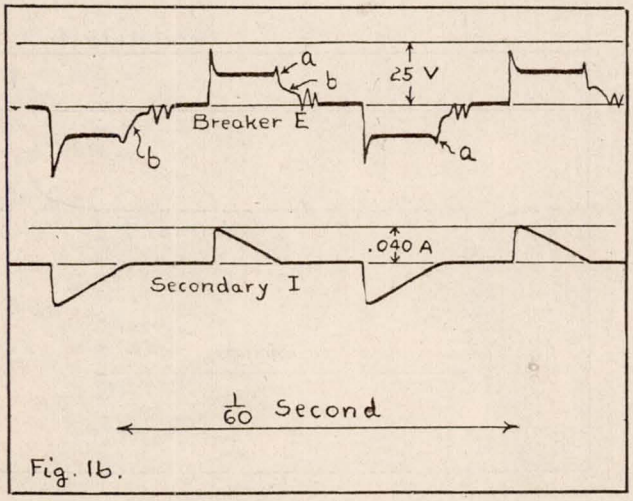


Fig. 16.

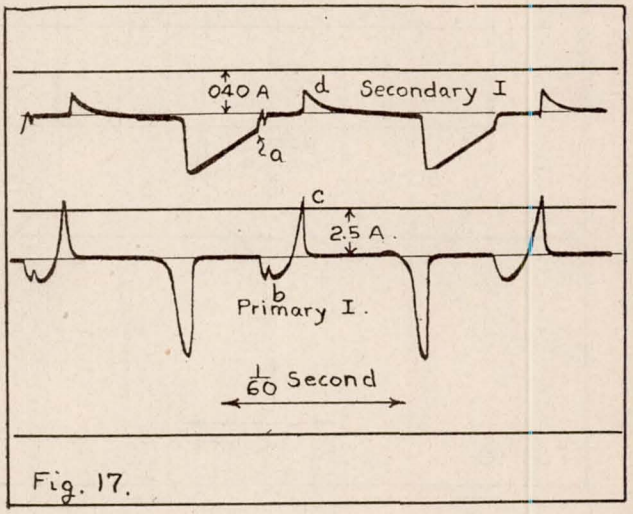


Fig. 17.

In the actual magneto the primary resistance materially reduces the generated current and the actual flux at break is (as shown in plot 20) considerably less than the maximum open circuit flux.

It should be noted that there is a very considerable difference in the operation of a magneto at low and at high speeds. In the former case, the primary current is limited chiefly by the resistance of the windings and has approximately the same wave form as the generated voltage. The maximum current reached is proportional to the speed and is small so that the total energy stored magnetically is also small. Consequently at "break" nearly all of this energy must be transferred to the electrostatic capacity of the windings and condenser before the voltage is sufficiently high to jump a normal spark plug gap. At high speeds on the other hand the current is limited by the inductance of the circuit and is nearly independent of speed. The current and magnetic energy are very much greater and only a negligible part of this energy is expended at "break" in charging the capacities to the breakdown voltage. This effect is shown in plot 21 in which the current generated in the short-circuited primary at various speeds is plotted against speed. The lower curve shows the effective (root-mean-square) value as observed with a hot wire ammeter, and the upper curve the maximum value of the current wave from oscillograms. It is evident that above 400 revolutions per minute the current is large and independent of the speed while at low speeds the current is smaller and of more peaked wave form. This is also shown by a comparison of figures 5 and 6 which show the difference in the wave form of the primary current on short circuit at low and high speeds.

The primary current finally attained at break, I_B, is of the greatest importance in determining the performance of the apparatus. It can be determined directly by an oscillograph by inserting a shunt of about 0.025 ohm in series with the primary and connecting the oscillograph vibrator across this shunt. This method has the disadvantage of introducing resistance into the circuit and thereby disturbing conditions. At high speeds this disturbance is entirely negligible, for the current is then limited by the inductance rather than the resistance of the circuit. At low speeds, however, the resistance predominates and the error might amount to 5 per cent or 10 per cent at very low speeds. The current waves in figures 4 to 19 were obtained in this manner.

Other methods for determining the primary current wave are based on first obtaining the open-circuit voltage wave or the flux wave and then computing the current by a step-by-step process.

Armagnat [1] and Young [2] have developed the following equations for this purpose from the fundamental equation

$$e = Ri + L\frac{di}{dt} \tag{1}$$

which applies to any inductive circuit. By integrating this over a short interval $\Delta t = t_2 - t_1$ they obtain

$$\int_{t_1}^{t_2} e\,dt = R\int_{t_1}^{t_2} i\,dt + L(i_{t_2} - i_{t_1}) \tag{2}$$

Letting $A = \int_{t_1}^{t_2} e\,dt$ = area under the voltage-time wave between t_2 and t_1, and assuming that i can be taken as changing linearly over the short time interval considered we get

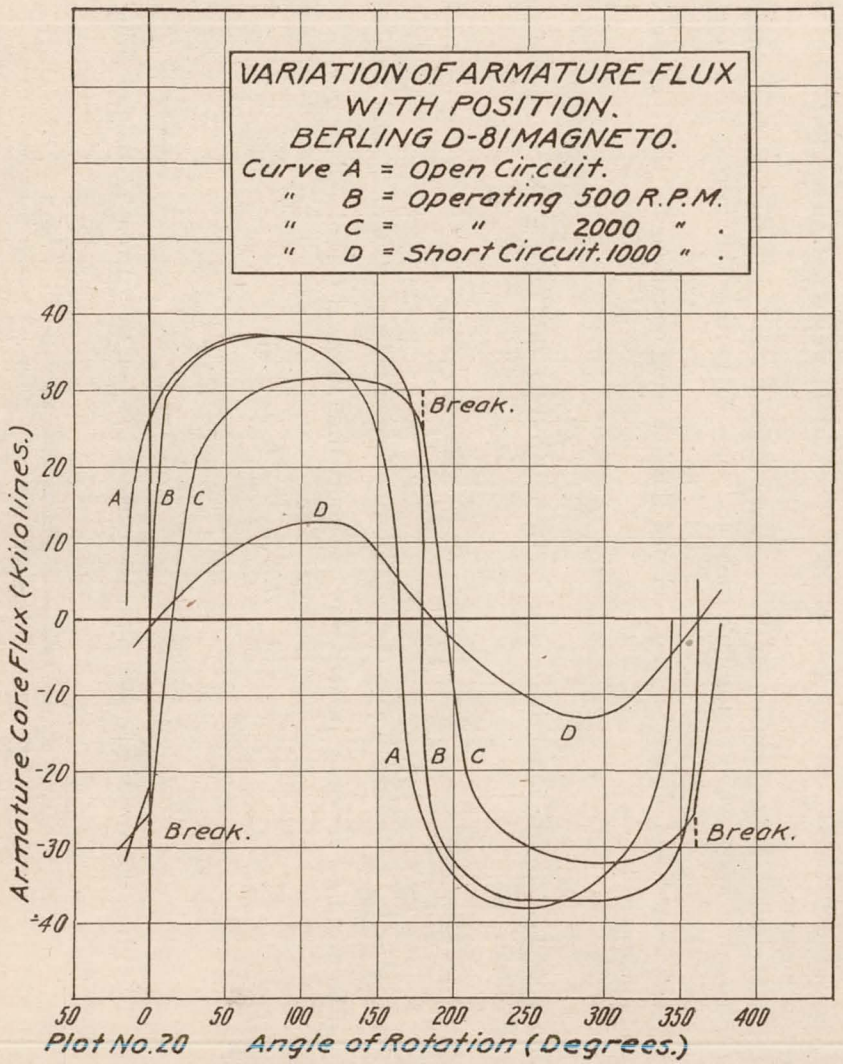
$$A = R\Delta t\frac{i_{t_2} + i_{t_1}}{2} + L\,(i_{t_2} - i_{t_1}) \tag{3}$$

or

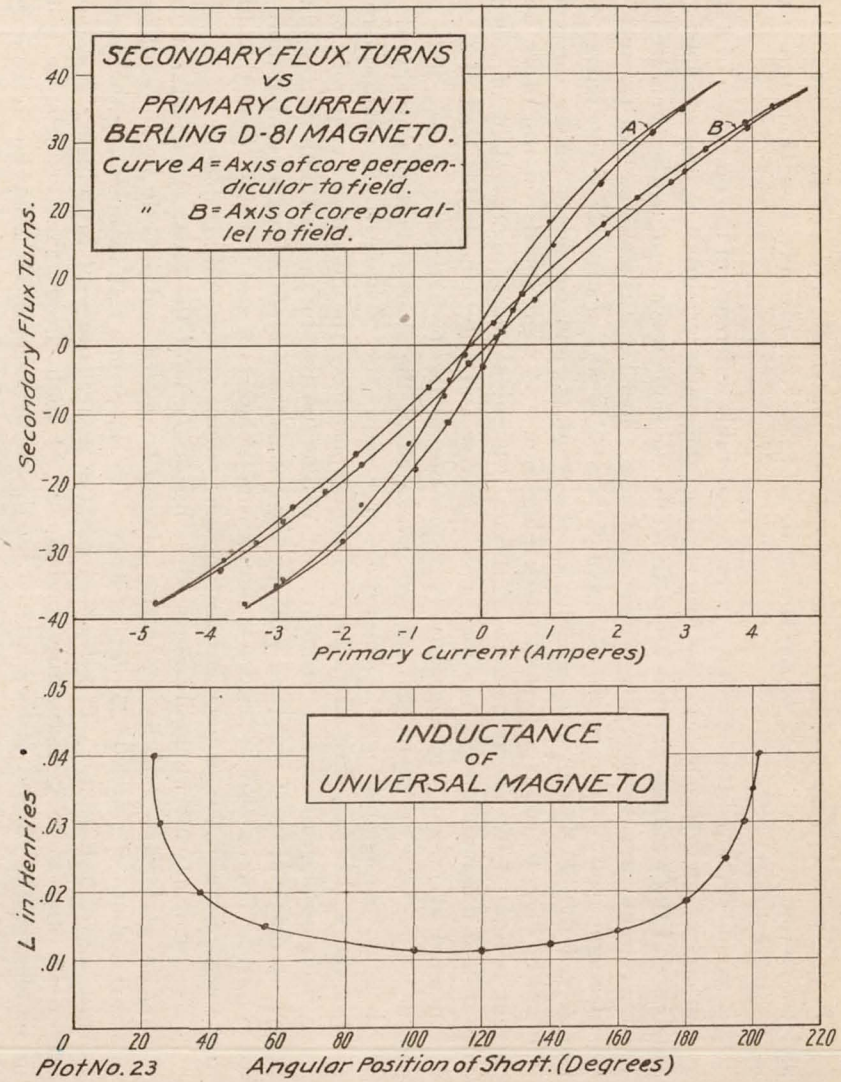
$$i_{t_2} = \frac{2A + i_{t_1}(2L - R\Delta t)}{2L + R\Delta t} \tag{4}$$

This gives the working equation for the current i_{t_2} when the current at the preceding time i_{t_1} is known.

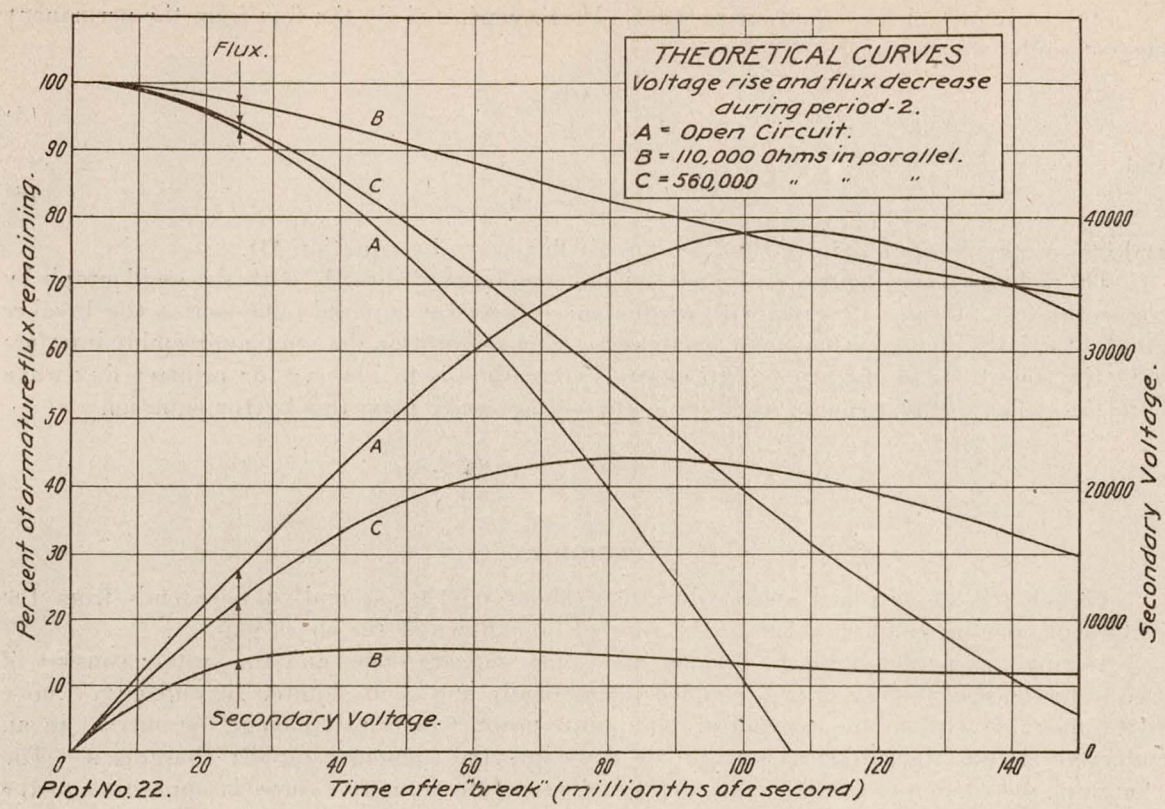
[1] Armagnat, H. Rev. Electrique 23, p. 321-333, 1915. Electrician 76, p. 865-899, 1916.
[2] Young, A. P. Aeronautical Jour., pp. 142-252, 1917. Automobile Engineer, March, 1915.



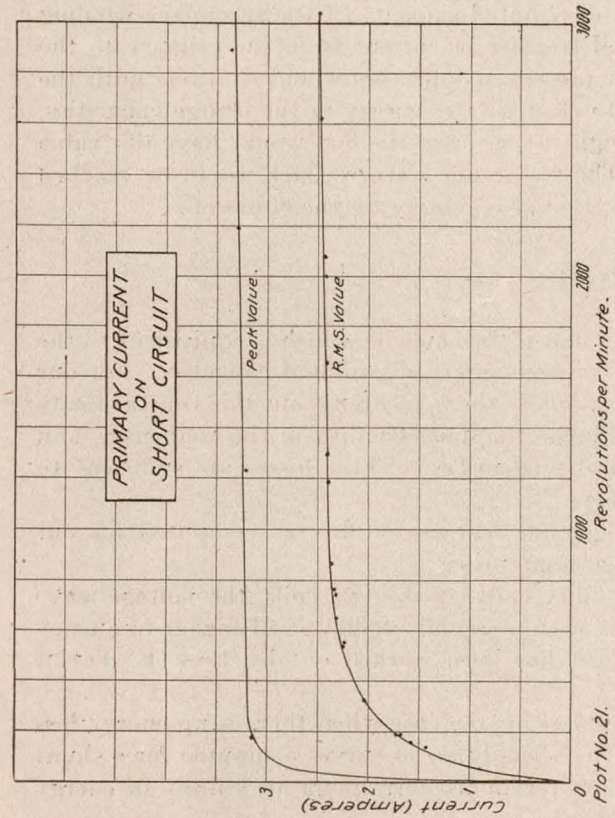
Plot No. 20



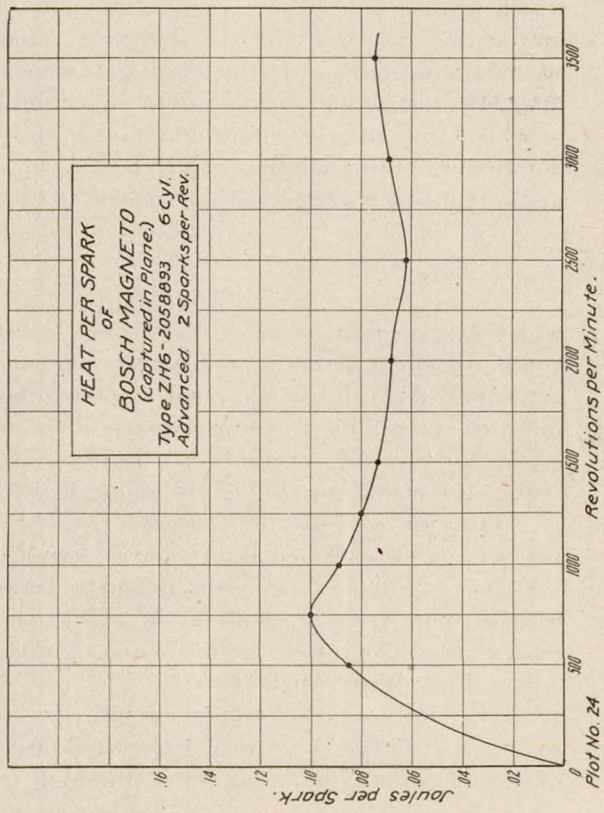
Plot No. 23



Plot No. 22.



Plot No. 21.



Plot No. 24

Since e in the above equation is the E. M. F. generated by the flux from the permanent magnets only, we may write

$$e = \frac{-N\,d\varphi_m}{dt} \tag{5}$$

and

$$A = N\,(\varphi_{t_1} - \varphi_{t_2}) \tag{6}$$

and hence may compute i from the open-circuit flux wave by equation (4).

The voltage wave (figures 8, 9, and 10) may be observed directly with the oscillograph by connecting the vibrator in series with a resistance of several hundred ohms across the breaker points (the latter being permanently insulated). This connection does not appreciably interfere with the conditions of operation. An alternative method is to observe the primary flux wave with the ballistic galvanometer and obtain the voltage wave from this by the equation

$$E = -N\frac{d\varphi}{dt} = -N\omega\frac{d\varphi}{d\alpha}$$

PERIOD 2.

Period 2 is of extremely short duration (about 0.00002 second) and extends from the instant of opening of the breaker to the time of breakdown of the spark gap.

During this period both the breaker and spark gap are open, and the system consists of two inductance coils very closely coupled magnetically and each shunted by capacity. Since it is impossible without the expenditure of infinite power to abruptly change the current in an inductive circuit, the primary current now flows into the condenser rapidly charging it. The charge in the condenser offers a continually increasing electromotive force in opposition to the primary current, which therefore decreases at a constantly increasing rate. The decrease of flux resulting from this decrease of primary current generates an E. M. F. in the secondary winding which in turn sends a charging current into the distributed capacity of the secondary winding and leads. The net effect is, therefore, a partial transfer of current from the primary to the secondary windings. If the spark gap were not present this process would continue until the magnetic energy had been entirely converted into electrostatic energy in the charge capacities, at which time the currents would have been brought to zero and the flux would have the value determined by the permanent magnets alone. The maximum voltage which would be reached at this time, if energy losses are neglected, is given approximately by the equation.

$$E = I_B\sqrt{\frac{L}{C}}$$

where L is the inductance of the primary winding and C the capacity which is equivalent to the combined effect of both the primary condenser and secondary distributed capacity. For our typical example this would reach 70,000 volts. Actually there is throughout this time a steady drain of energy due to the resistance of the windings, the dielectric loss in the condenser, and especially the eddy currents in the iron core and pole pieces. These losses are sufficient to reduce the maximum voltage to about 40,000 volts.

The curves in plot 22 show the rise of voltage and decrease of flux as computed for our typical example after making certain simplifying assumptions.

If account is taken of the magnetic leakage flux between the two coils, the voltage wave will be found to be a combination of that shown with a second oscillation of higher frequency and smaller amplitude. The theory of this effect has been worked out by Prof. E. Taylor Jones (Phil. Mag., August, 1918).

The curves marked "open circuit" are computed for the case when there is no energy loss except that in the resistance of the windings. The second pair of curves computed for a shunt of 560,000 ohms connected across the high tension terminals correspond to a drain of energy

approximately equal to that to be expected from eddy currents. The third pair of curves correspond to a shunting resistance of 110,000 ohms, which might occur with a partially fouled spark plug. The assumption upon which all these curves have been constructed is that the spark gap does not break down. In normal operation, however, the spark gap breaks down at about 6,000 volts, and consequently new circuit conditions are introduced before the resultant flux has decreased materially from its value at break.

In the above discussion it is assumed that the breaker succeeds in opening the circuit without sparking at the contacts. If an arc occurs at break, some of the energy is dissipated then, and the rate of decrease of primary current, and consequently the induced secondary voltage, is much less. Figures 14 and 15 show the excessive arcing at the breaker which occurred when a special cam was used giving a very slow rate of separation of the breaker points. The contacts separate at *a*, but the arc maintains the current until *b*, when it finally breaks and a considerably reduced spark results.

PERIOD 3.

When the gap has broken down it affords a conducting path, and the charged secondary capacity and leads immediately discharge through it. The exact conditions existing in the spark, particularly immediately after break down, are still obscure, and it is possible that this first discharge may be oscillatory and of high frequency.

Tests made by loosely coupling a sensitive wave meter to the secondary circuit of a magneto have shown no indication of resonance with any oscillations within the range between 30,000 and 1,000,000 cycles, although the apparatus used was sufficiently sensitive to have detected a steady oscillation of 0.2 milliampere throughout the range. A circuit formed by connecting a loop from one point of the distributor to ground was found to absorb oscillations of frequencies from 3,000,000 to 10,000,000 cycles per second for various configurations of the loop, but no such absorption was detected at frequencies from 2,000 to 30,000 cycles per second. Any oscillations which may have been present must therefore have been very feeble or very highly damped.

In addition to this discharge of the leads, the current increases rapidly in the secondary, since it is now practically short-circuited by the gap; and the primary current simultaneously decreases at such a rate that the total ampere turns linking the main flux are maintained with little loss. The charged primary condenser hastens the decrease of primary current and ultimately reverses it for a short time while the condenser energy is being shifted to the secondary side. The dissipation of energy in the gap, however, is probably sufficient to damp out any oscillations from this condenser.

The net results of the three simultaneous processes during this period are, therefore, (*a*) the discharge into the gap of the energy stored in the capacity of the leads; (*b*) the complete stopping of the primary current and the formation of a secondary current giving approximately the same ampere turns; and (*c*) the dissipation in the windings and gap of the energy in the primary condenser. The duration of the period is of the order of one cycle of an oscillation, determined by the primary condenser and the leakage inductance of the windings (approximately 0.00005 second). The energy discharged into the gap during this time is about 0.002 joules, which recent measurements indicate is just about sufficient to ignite an explosive mixture. It is therefore probable that this period 3 is the one fundamental to ignition.

PERIOD 4.

Period 4 extends from the establishment of the secondary current in a steady arc across the spark gap to the extinction of the spark. During this time there exists across the gap a steady discharge which lasts for a considerable time (0.003 second in the case of a 5-mm. spark gap in air). It has been found experimentally that the voltage drop in the gap is roughly constant during this entire period, as is shown by oscillograms such as figure 16. The capacities therefore remain with a small charge and have little effect on the phenomena. The energy dissipated in the gap is supplied by the decay of the secondary current in the coil, and since the voltage is approximately constant and

$$E = -L\frac{di}{dt}$$

the current drops off linearly with time. The instantaneous resistance of the spark $\left(R = \frac{E}{I}\right)$ is thus seen to increase rapidly from about 8,000 ohms at the beginning of period 4 to a very high value at the end. It is during this period that the major part of the energy of the spark is liberated in the gap.

In the case of the induction coil of a battery system the magnetic field is the only source of energy and the heat dissipated in the gap may be computed with a fair degree of accuracy from the stored energy $\frac{1}{2} L I_B^2$ by correcting for the I^2R loss in the secondary winding. In a magneto, however, particularly when operating at full advance, the voltage generated by the rotation of the secondary winding in the magnetic field is comparable with the sustaining voltage across the gap; and a very considerable amount of energy is thus forced into the secondary by the rotation of the armature. This may cause a very marked "hump" in the secondary current wave, such as appears at *c* in figure 15. The E. M. F.'s in the circuit satisfy the equation:

$$E_r - L_2\frac{di_2}{dt} = E_s + R_2 i_2$$

where E_r is the voltage generated by the rotation of the armature in the magnetic field and E_s is the voltage drop required to sustain the arc between the gap terminals. The corresponding energy equation may be written:

Energy derived from rotation + energy released by breaking primary = heat in spark + loss in secondary copper.

The following table gives typical values of these quantities computed from oscillograms together with the spark heats observed with a calorimeter in three particular cases:

	Magneto.		Battery and coil.
	Advanced.	Retarded.	
Magnetic energy	0.05	0.15	0.019
Rotational energy	.19	.00	.00
Total	.24	.15	.019
Heat in spark (calorimeter)	.15	.08	.016
Heat in spark oscillograph	.15	.11	.014
Secondary copper loss	.04	.03	.001
Stray losses (by difference)	.05	.01	.004
Total	.24	.15	.010

In the case of iron-clad circuits such as are here considered the term "inductance" is somewhat vague and is difficult to define precisely. It evidently varies with the angular position of the rotor, with the current flowing, and (because of eddy currents) with the rate of change of current. It is possible, however, with the armature clamped in any given position, to determine by the ballistic galvanometer the change in flux turns corresponding to any given change in current, and the equivalent inductance can then be computed. Plot 23 shows hysteresis loops determined in this way. This illustrates the relation between the secondary flux turns and the primary current for a shuttle-type magneto when the armature is clamped in the positions of zero flux and maximum flux, respectively. In the first position, the permanent magnets send no flux through the armature core, and the loop was obtained in the usual manner with currents in both directions. In the second position the magnets alone would produce the flux indicated by the apex of the loop. The curve was obtained by applying currents opposing the magnets and noting the corresponding changes in flux. From curves of this kind it is possible to establish approximately the equivalent inductance corresponding to any given conditions.

A much simpler method is to measure the effective inductance of the windings while clamped in any position with alternating current, using either a bridge or a voltmeter-ammeter-wattmeter method. A typical curve obtained in this way is shown in plot 24. This method was used in obtaining the values given in the preceding table.

The stopping of the steady arc and consequently the end of period 4 may be due to one or the other of two causes. These are (*a*) the exhaustion of the energy supply which results in the gradual reduction of the current to zero and the cessation of the arc, as is shown in figures 11 and 14, or (*b*) the closing of the primary breaker which has the effect of quickly extinguishing the spark, as is shown at *a* in figure 13. In the former case there is at very small currents a rather rapid increase of the sustaining voltage (as at *a*, figure 16) to a value which at the instant of cessation of the spark may be double its normal value. The secondary current consequently drops to zero at a somewhat more rapid rate than during the major portion of period 4. The "natural" or uninterrupted dying out of the spark usually occurs in magnetos operating at moderate speeds and with reasonably long spark gaps, and almost invariably occurs in battery systems. It may be considered as the normal mode of operation of the system.

Owing to the large number of variables (such as current at break, rotational energy, and extinction of the spark by the closing breaker) which affect the total heat liberated in the gap, it is impracticable to accurately predetermine the heat per spark for any particular condition. Plot 25 shows how this heat (observed calorimetrically) varies with magneto speed for a particular German Bosch ZH6 magneto.

PERIOD 5.

If the magneto is operating at very high speed or on a very short spark gap, the primary contact breaker may close before the spark has died out. In this case the circuit conditions are again changed and an additional transition period 5 must be considered. The sequence of events during this period is quite closely the inverse of that occurring during period 3. The decreasing flux caused by the decreasing secondary current induces an E. M. F. in the primary turns which rapidly builds up current in the now short-circuited primary winding. This increase of current in turn, by its mutual induction on the secondary turns, rapidly decreases the secondary current. The net effect is that the remaining ampere turns linking the main flux are transferred from the secondary back to the primary and the spark is extinguished. At the same time the primary condenser which had been charged to the small voltage given by the quotient of E_s divided by the ratio of turns, discharges through the contact, and later the secondary capacity is similarly discharged. The entire duration of the period is extremely short and is of the order of 0.00005 second.

PERIOD 6.

Period 6 may be defined as lasting from the end of period 5 until the armature has rotated to the position where it receives maximum flux from the magnets. During this time the primary current continues to decay approximately according to the exponential law

$$I = I_o e^{-\frac{R}{L}t}$$

where R and L are the resistance and inductance of the primary circuit and I_o is the current at the end of period 5. The value of $\frac{R}{L}$ for this circuit is much smaller than for the circuit formed of the secondary winding and spark, so that the rate of decrease of current is quite slow, and an appreciable current may be flowing, when the position of maximum flux is reached, and period 1 of the next alternation begins.

In some cases this interference may be so great as to cause the succeeding spark to miss fire as shown in figure 17. In cases where the spark dies out before the closing of the breaker, period 6 follows immediately after period 4 and the circuit is practically free from current throughout the period.

During the interval after the dying out of the spark and before the closing of the breaker there may remain a small amount of local eddy currents in the iron core and pole pieces. As these decay exponentially they induce in the winding an appreciable E. M. F. such as is shown at *b* in figure 16. After the closing of the breaker, this E. M. F. reestablishes a small primary current in the original direction, as shown at *a* in figure 12. These minor effects afford possible but rather inaccurate means of estimating the magnitude of the eddy currents and hence their much more serious effect during period 2.

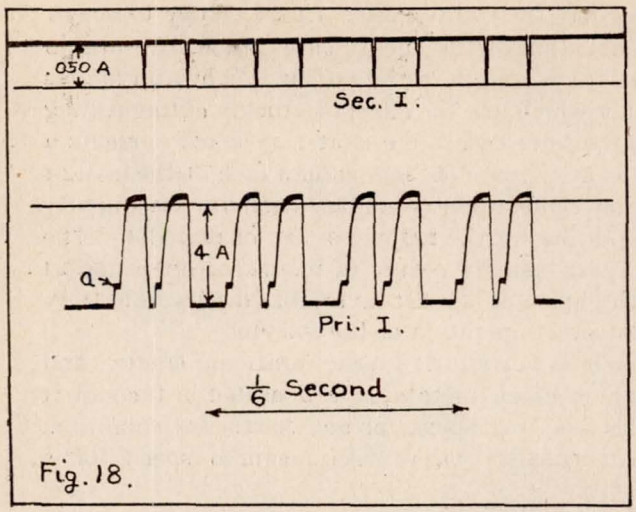


Fig. 18.

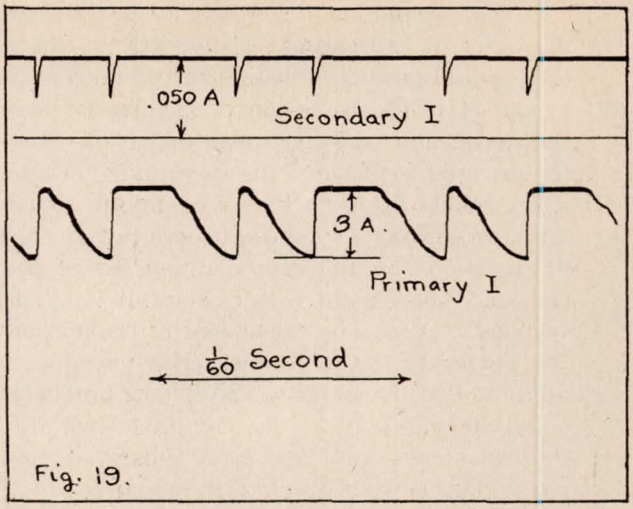


Fig. 19.

BATTERY SYSTEMS.

In the case of the usual arrangements of battery systems, the typical connections of which are shown in figure 2, period 1 may be defined as lasting from the closing of the primary contact to its opening, and is quite closely analogous to period 1 for a magneto. The primary current builds up during this period approximately according to the equation

$$I=\frac{E}{R_p}\left(1-e^{-\frac{R_p}{L_p}t}\right)$$

but may depart somewhat from this because of the varying permeability of the iron core and the heating and consequent change in resistance of part of the circuit. This rise of current is shown in figures 18 and 19. In the so-called "closed circuit" type of system, period 1 lasts during a constant angular motion of the engine shaft and its duration is consequently shorter the higher the speed. In the "open circuit" systems the circuit is closed for a constant time interval at all speeds and this interval is usually much less than required for the current to approach the constant value $\frac{E}{R}$.

The energy which can be stored in the magnetic field during this period is usually decidedly less than that obtained with a magneto at normal speed because of the lower voltage available. The battery system usually operates on 6 or 12 volts, while a magneto may give a primary peak voltage from 50 to 100 volts at high speed. The battery, however, maintains its voltage at all speeds while the magneto may give only 4 or 5 volts peak at 100 revolutions per minute.

Periods 2, 3, and 4 are practically the same in both battery and magneto systems except that the effect of the rotational energy is absent in the battery system, and the spark heat for the same inductive energy is correspondingly reduced. Owing to this small energy content, the spark almost invariably dies out before the closing of the contact for the next spark, as shown in figures 18 and 19. Consequently, period 5 is absent and the circuit is entirely dead during period 6.

CONCLUSIONS.

It appears from the above analysis that periods 1, 4, and 6 are of comparatively long duration and the phenomena occurring therein are relatively slow and well understood. Periods 2 and 3, on the other hand, are extremely short, and very little experimental data are available to confirm or disprove the theoretical speculations as to what takes place. These two periods are, however, in a sense the most important of the entire cycle since it is the rise of voltage in period 2 which determines whether or not a spark passes at all, and the actual ignition of the mixture probably occurs during period 3. The usual forms of oscillograph are entirely unable

to analyze processes of such short duration, but the Braun tube (or cathode ray oscillograph) seems to afford a promising tool for studying these phenomena.

It seems evident that the distributed capacity of the secondary winding and high tension leads is of great moment in determining the maximum voltage attained in period 2. Also the eddy currents cause a very serious drain of energy, particularly in magnetos with solid pole pieces, though their effect is probably quite small in battery systems in which the magnetic circuit can be thoroughly laminated. Convenient methods of measuring these two effects are greatly needed. Preliminary measurements of the apparent resistance and inductance of the windings with an alternating current bridge at frequencies up to 3,000 cycles throw some light on this problem, and if a convenient way of interpreting the results can be worked out, this method may prove useful.

The requirements of an ignition system are quite different from almost any other form of electric generating system and are in some respects conflicting in character. A high voltage is required to jump the spark gap through the compressed gas in the engine cylinder. While this is usually only 5,000 to 6,000 volts, it may be very materially increased by oil films on the electrodes and a cold and consequently dense charge when starting an engine. Such a high voltage, of course, requires a large number of secondary turns. On the other hand, the spark plugs frequently become coated with a conducting film of carbon, which drains the energy during period 2 in much the same manner as the eddy currents. It then becomes necessary to supply such a large current that the IR drop in the carbon deposit is equal to the sparking voltage of the gap in order to produce a spark. Since the secondary current during periods 3 and 4 is limited to the value which produces the same ampere turns around the armature core as did the primary current before "break," this second condition requires a small number of secondary turns.

Recent measurements at the British National Physical Laboratory indicate that the actual energy required for ignition is very small compared to that furnished by any commercial form of ignition system, and any excessive amount of power is slightly detrimental in that it increases burning of the spark plug and contact breaker terminals. The paradoxical requirement is therefore for a system furnishing large current and voltage but small power.

A possible solution to this problem lies in the use of a suitable subsidiary spark gap and condenser as used in the Lodge arrangement and similar high frequency systems, in which the voltage is made as great as possible and the large current required by a fouled plug is obtained by the sudden discharge of a condenser through the auxiliary gap. The presence of the condenser, however, tends to reduce the maximum voltage attainable and to some extent defeats its own purpose. Report No. 57 gives the results of preliminary work on this type of device.

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REPORT No. 58.

PART II.

TRANSFORMATION RATIO AND COUPLING IN HIGH TENSION MAGNETOS.[1]

By F. B. Siesbee.

RÉSUMÉ.

This report describes a convenient method for measuring the ratio of turns of high tension magnetos or induction coils. Two resistances are connected between the high tension terminals and ground, and a galvanometer is connected between the junction of the resistances and the junction of the primary and secondary windings. The resistances are then adjusted until no kick of the galvanometer occurs when the magnetic flux through the coils is suddenly varied. This variation in flux may be made by moving the rotor of the magneto or by interrupting a current in either winding. From measurements by both methods an estimate of the magnetic leakage and coupling coefficient is obtained. Results obtained on various magnetos by this method are given. The ratios are usually between 40:1 and 70:1, and the magnetic leakage flux is only 2 to 4 per cent of the flux common to both windings.

INTRODUCTION.

A knowledge of the ratio of turns or more strictly the ratio of magnetic linkages between the primary and secondary windings of magnetos or spark coils is frequently needed, both in predicting the performance to be expected from a given coil and in analyzing the results of oscillographic tests, etc. The method which is described in this report is similar to the alternating current methods used in obtaining the ratio of transformers and no claim is made for novelty in respect to it. It has, however, been found very useful in connection with the investigation of ignition problems and is capable of all the accuracy needed in such work.

PROCEDURE.

For simply obtaining an approximate value for the ratio of turns the connections shown in figure 1_a are used. Here S and P are the secondary and primary windings of the magneto or induction coil, respectively. R_1 and R_2 are noninductive resistances, one of which should be adjustable. G is preferably a ballistic galvanometer of fairly long period, but almost any type of galvanometer can be used. In obtaining the results which are given in the later sections of this report a small Paul unipivot galvanometer of about seven ohms resistance was used. In case only moderate accuracy is needed, any low range direct current milliammeter or millivoltmeter is suitable. With the connections as shown the magnetic flux through the windings is suddenly varied, as by rotating the armature 180 electrical degrees, and the resulting throw of the galvanometer noted. The resistance R_1 (or R_2) is then varied until this throw is reduced to zero. When this condition is attained the ratio of flux turns is given by the formula

$$n_m = \frac{N_s \Delta\varphi_s}{N_p \Delta\varphi_p} = \frac{S+R_1}{P+R_2} = \frac{N_s}{N_p}, \text{ approx.} \qquad (1)$$

Here N_s and N_p are the primary and secondary turns, respectively, and $\Delta\varphi_s$ and $\Delta\varphi_p$ are the respective changes in the flux linking the two coils, and are of course nearly equal in value. S, P, R_1 and R_2 are the values of the corresponding resistances. Care must be taken that the

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 16.

resistances of the circuit remain constant when the flux is varied, and to secure this condition the carbon brushes which are usually used in magnetos must be replaced with metal brushes or flexible wire connections.

MATHEMATICAL THEORY OF METHOD.

The E. M. F. induced in the primary by the changing flux is

$$E_p = -N_p \frac{d\varphi_p}{dt} \tag{2}$$

and the secondary E. M. F. is similarly

$$E_s = -N_s \frac{d\varphi_s}{dt}. \tag{3}$$

Applying Kirchhoff's laws to the two circuits shown in figure 1_a we obtain the equation

$$-N_s \frac{d\varphi_s}{dt} + i_s(S+R_1) + (i_s - i_p)R_g = 0 \tag{4}$$

$$-N_p \frac{d\varphi_p}{dt} + i_p(P+R_2) + (i_p - i_s)R_g = 0 \tag{5}$$

where R_g is the resistance of the galvanometer and i_p and i_s are the instantaneous currents in the two circuits.

Integrating these with respect to time from t_1 to t_2 gives

$$-N_s\Delta\varphi_s + (S+R_1)\int_{t_1}^{t_2} i_s dt + \int_{t_1}^{t_2} R_g(i_s - i_p)dt = 0 \tag{6}$$

$$-N_p\Delta\varphi_p + (P+R_2)\int_{t_1}^{t_2} i_p dt - \int_{t_1}^{t_2} R_g(i_s - i_p)dt = 0 \tag{7}$$

where $\Delta\varphi_s$ and $\Delta\varphi_p$ are the changes in flux between the initial and final conditions. Since R_g is constant, it can be taken outside of the integral and the third term in each equation becomes

$$R_g\int_{t_1}^{t_2}(i_s - i_p)dt = R_g\int_{t_1}^{t_2} i_g dt \tag{8}$$

Now, if the time interval during which the change occurs is short compared with the natural period of the galvanometer, the deflection will be proportional to $\int i_g dt$, and since the resistances were adjusted to give zero deflection we have

$$\int_{t_1}^{t_2} i_g dt = 0, \text{ or } \int_{t_1}^{t_2} i_s dt = \int_{t_1}^{t_2} i_p dt. \tag{9}$$

Dividing equation (6) by equation (7) gives

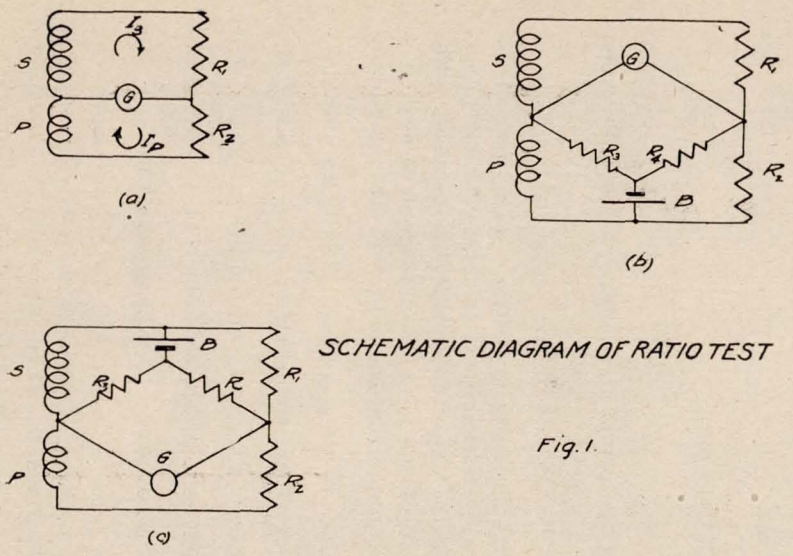
$$\frac{N_s\Delta\varphi_s}{N_p\Delta\varphi_p} = \frac{(S+R_1)\int_{t_1}^{t_2} i_s dt}{(P+R_2)\int_{t_1}^{t_2} i_p dt} \tag{10}$$

or by equation (9)

$$\frac{N_s\Delta\varphi_s}{N_p\Delta\varphi_p} = \frac{S+R_1}{P+R_2}. \tag{11}$$

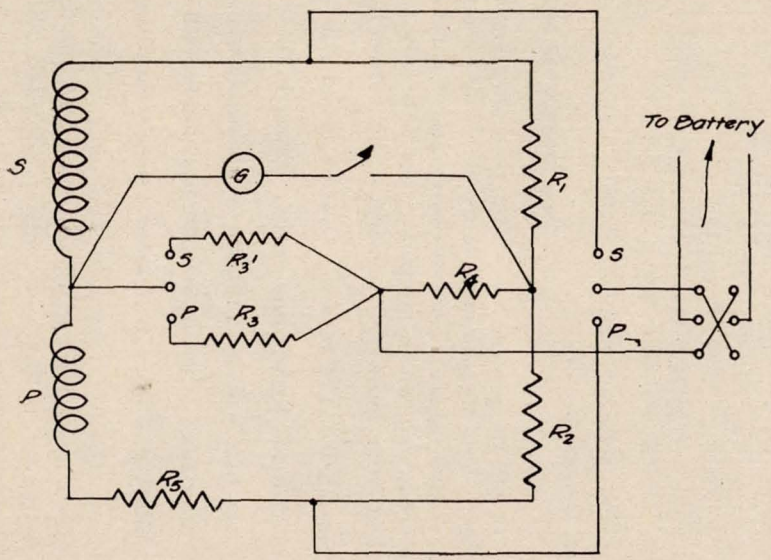
MEASUREMENTS WITH CURRENT IN COILS.

The validity of the method as just described does not depend upon the manner in which the change of flux $\Delta\varphi$ is produced, and this can, if desired, be obtained by passing a current through one of the coils and interrupting or changing the value of this current. In this case, however, while the current is flowing there will be an IR drop due to the resistance of the coil which will tend to cause a permanent deflection of the galvanometer and will thus interfere with the measurements. This can be eliminated by using a Wheatstone bridge arrangement, as



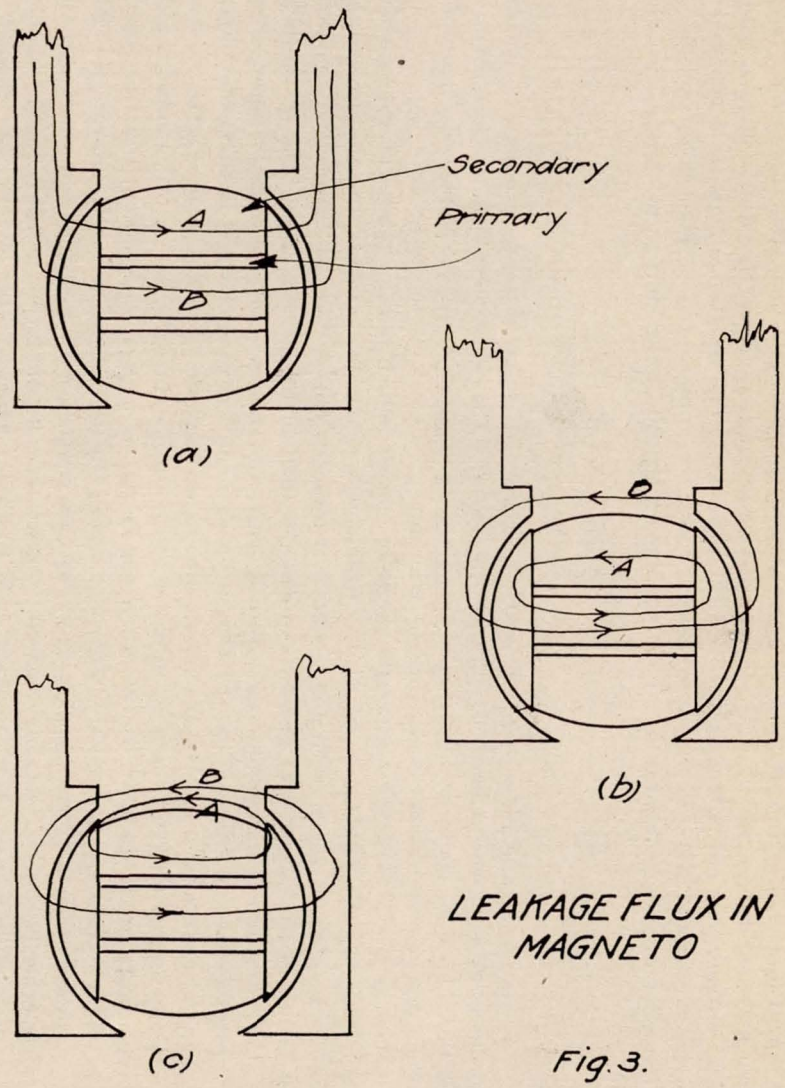
SCHEMATIC DIAGRAM OF RATIO TEST

Fig. 1.



CONNECTIONS FOR RATIO TEST

Fig. 2.



LEAKAGE FLUX IN MAGNETO

Fig. 3.

shown in figure 1_b. Here R_3 and R_4 are auxiliary resistances which, together with P and R_2, form a Wheatstone bridge. The procedure is to first adjust R_4 so that this bridge is balanced while a steady current is flowing through the primary. The resistance R_1 is then adjusted until the galvanometer gives no throw when this current is interrupted. When a balance has been obtained under both conditions, it can be shown by reasoning similar to that in Section III that

$$n_p = \frac{N_s \Delta\varphi_s}{N_p \Delta\varphi_p} = \frac{S + R_1}{P + R_2}.$$

A similar arrangement can, of course, be used to send current through the secondary windings, as is shown in figure 1_c. Since the value of the resistances S and P are involved in the final formula, these bridge circuits serve very conveniently, if the values of R_3 and R_4 are known, to measure the resistances of the windings.

Owing to the fact that the windings are of copper, which rises in temperature considerably when carrying the working current, it is usually convenient to insert a manganin resistance of about one ohm in series with the primary winding. This serves to reduce the temperature coefficient of the circuit and greatly reduces the drift of the galvanometer due to the heating.

In the simple arrangement shown in figure 1_a the presence of a condenser shunted around the primary has no effect upon the measurements since it is uncharged both at the beginning and end of the operation. When sending current through the windings from a battery, however, the condenser is charged initially to a voltage equal to the IR drop in the winding, and this energy adds to the ballistic throw when the circuit is broken. In actual practice, however, this effect is entirely negligible. Figure 2 shows the circuits as actually used at the Bureau of Standards in which the double throw switches marked S—P serve to connect the auxiliary bridge arms for use in sending current through the secondary or primary coil, respectively, and the simple arrangement in figure 1_a is obtained when all the switches are opened. The values of resistances used are given in the following table:

R_1 = dial box, 1000's to 10's.
R_2 = 100 ohms fixed.
R_3 = 5 ohms fixed.
R_3' = 1000 ohms fixed.
R_4 = dial box, 1000's to 1's.
R_5 = 1 ohm fixed.

This circuit is supplied from 8 volts when using the primary winding and 80 volts when using the secondary.

DISCUSSION OF MAGNETIC CIRCUIT.

It will be observed that this method gives, strictly speaking, the ratio of flux turns in the two coils and not the ratio of turns themselves and a consideration of the magnetic circuit, as indicated in figure 3, shows the values of this ratio to be expected in the various cases. For the circuits shown in figure 1_a, in which only the field of the permanent magnet is used, it is evident from figure 3_a that some of the flux will pass through the secondary coil without linking the primary. The ratio n_m thus observed will therefore be greater than $\frac{N_s}{N_p}$. If the measurement is made by sending current through the primary, then, as shown in figure 3_b, all of the primary flux will not link the secondary, and the observed ratio n_p will be less than $\frac{N_s}{N_p}$. On the other hand, if the measurement is made with current through the secondary, then some of the secondary flux will not link the primary, and the observed ratio n_s will be greater than $\frac{N_s}{N_p}$. In either of the last two cases, the departure from the ratio of turns will be greater when the magnetomotive force of the coil aids that due to the permanent magnets than when it opposes it, as the iron is then more nearly saturated and less permeable. Typical results on a magneto of the shuttle core type which shows these variations in apparent ratio is given in Table I.

TABLE I.—*Observed flux-turn ratios in Berling S-18, magneto shuttle core type.*

Position of armature axis.	Ratio measured by—		
	Current in primary n_p.	Magnet flux n_m.	Current in secondary n_s.
Parallel to flux aiding magnets	55.6	.....	59.4
Perpendicular to magnet flux	56.4	57.1	57.4
Parallel to flux opposing magnets	55.9	.....	57.8
Mean	56.0	57.1	57.9

$$\sqrt{\frac{L_2}{L_1}} = 56.9 \qquad K = \sqrt{\frac{M^2}{L_1 L_2}} = .984.$$

If the windings are regarded as independent coils having inductances L_1 and L_2, and a mutual inductance M, then we may write

$$n_p = \frac{M}{L_1} \text{ and } n_s = \frac{L_2}{M}$$

The coefficient of coupling k, defined as $\sqrt{\frac{M^2}{L_1 L_2}}$, is therefore given by $\sqrt{\frac{n_p}{n_s}}$. The ratio of the inductances is similarly given by $n_p n_s$.

As will be seen by reference to the data given in Table II, the value of k is very nearly unity, which means that the energy is very easily transferred from primary to the secondary circuit at the instant of break. The effect of the few per cent by which k departs from unity upon the operation of the magneto is very complex, but the energy involved in the leakage flux is obviously small compared with the total amount of energy stored.

RESULTS ON VARIOUS MAGNETOS.

The following table gives the result of measurements made by the method outlined above on a number of magneto and ignition coil systems. The values of the observed ratio with all three connections are given, also the coefficient of coupling and the square root of the ratio of secondary to primary inductance. This latter figure is probably the best estimate available of the true ratio of turns for each winding.

TABLE II.

Magneto.	n_m	n_p	n_s	$\sqrt{\frac{L_2}{L_1}}$	k
American Bosch	48.9	47.4	49.7	48.6	0.977
Berkshire L. H	44.2	42.9	45.8	44.4	.968
Berkshire R. H	57.2	55.5	59.1	57.3	.970
B. T. H. No. 53769	67.8	65.3	67.8	66.6	.982
S. E. V. No. 2	68.3	66.1	68.4	67.2	.983
Berling D. 81	57.8	56.1	58.3	57.2	.980
Berling S. 18	57.1	56.0	58.2	57.1	.980
Lencke	36.5	35.6	36.7	36.2	.985
Dixie 800	57.0	56.2	58.4	57.3	.980
German Bosch	43.8	42.6	44.1	43.4	.983
Dixie 88	53.0	52.2	54.1	53.2	.983
Delco (Liberty)	.....	88.6	93.0	90.8	.953

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REPORT No. 59

GENERAL ANALYSIS OF AIRPLANE RADIATOR PROBLEMS

By H. C. DICKINSON, W. S. JAMES and R. V. KLEINSCHMIDT.

Bureau of Standards, Washington, D. C.

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REPORT NO. 59.

GENERAL ANALYSIS OF AIRPLANE RADIATOR PROBLEMS.

By H. C. Dickinson, W. S. James and R. V. Kleinschmidt.

The objects of this report are (1) to present the analysis of the problem on which the experimental work conducted at the Bureau of Standards is based, (2) to explain the technical terms used in the work, and (3) to show the relations between the various parts of the work which are dealt with in detail in other reports.

The function of a radiator is to dissipate heat, but while doing so, it will have certain adverse effects on the plane on which it is mounted. First, it will add to the weight; second, the conditions for obtaining the best transfer of heat from the metal surface to the air require that the air shall flow rapidly past the surface, and this condition causes head resistance; third, certain positions of mounting on the plane seriously obstruct the view of the pilot or observer. A fourth factor of special importance in military airplanes is vulnerability and liability to injury, either from accident or from enemy bullets. The last two factors, not being capable of measurement, have not been considered in this investigation.

STATEMENT OF THE PROBLEM.

The problem of design therefore becomes one of determining the type of structure, and the location on the plane, that shall give the radiator the cooling capacity required for the engine with which it is to be used, and at the same time shall result in a minimum adverse effect on the plane. The adverse effects due to weight and head resistance will be represented by the power absorbed in lifting and sustaining the weight and in overcoming the head resistance, and the fundamental criterion for an airplane radiator will be that its absorption of power shall be low, when it is of such size as to dissipate the required amount of heat.

It is necessary to state with some care what is meant by "power absorbed chargeable to the radiator." If it were possible to build and operate a plane without any radiator (or other construction to perform its function), a certain amount of power would be required to drive the plane through the air at a given speed. But the addition of the radiator may necessitate alterations in structure (such as the substitution of a flat-nose radiator for a stream-line nose or the enlargement of the fuselage in order to accommodate the radiator required), which will make the resistance of the plane greater than in the former case; and the radiator itself will add to the weight of the plane and will offer resistance to passage through the air. The difference between the power required to drive the plane as equipped with the radiator and that required to drive it at the same speed when designed without a radiator is the power absorbed chargeable to the radiator. It includes power absorbed due to (1) weight of the radiator; (2) pressure difference producing flow of air through the radiator (i. e., the head resistance of the core); (3) any increase in the resistance of the fuselage or other parts of the plane caused by changes in the condition of air flow around the parts, or by changes in the structure necessitated by the radiator; (4) pressure necessary to produce water flow through the radiator. Items (2) and (3) together constitute the head resistance chargeable to the radiator, as distinguished from the head resistance of the core. In the case of a nose radiator there is not only a change in the condition of air flow due to the air which passes into the fuselage and out through the louvres, but also a change in form of the fuselage, due to the flat (and sometimes enlarged) nose required to accommodate the radiator.

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THREE METHODS OF ATTACK.

There are three ways in which the problem may be attacked, namely:

1. A study of complete radiators on planes.

2. A study of types of radiator core and the methods of generalizing results to obtain the properties of complete radiators.

3. A study of the properties of single tubes, cells, or plates.

The first of these has been the basis of cut-and-try methods of determining whether a radiator will cool or not, but it has not been possible to consider the adverse effect on the plane by this method, except roughly. Weight is the only factor that can easily be measured, and it is found that in determining the power absorbed, weight may be of but small importance in comparison with head resistance. Although it might be possible to work out a method whereby complete data could be obtained from tests in flight, the expense and difficulty of making the necessary large number of tests on planes is so great that a simpler method has been chosen, which will allow a large number of types of core to be tested under widely varying conditions of use.

The study of types of core has therefore been selected as the basis of the experimental work, to be supplemented by such work on complete radiators in planes as may be required to verify the conclusions reached, and furnish needed data on the effect of location on performance. It has also been found advisable further to simplify certain portions of the work by studies on single tubes and plates.

The object of a laboratory study of types of core is to determine:

1. The structural characteristics of the core which determine its performance in any particular case, and the effect of these characteristics on performance.

2. The properties, or behavior, of the core when subjected to various conditions of use.

3. The conditions under which the core will operate when it is a portion of a radiator in any particular location on a plane.

STRUCTURAL CHARACTERISTICS OF A CORE.

The characteristics of a core which determine its behavior under given conditions of use have been taken to be:

1. Form and dimensions of air and water passages.

2. Depth of the core (measured in the direction of the air flow).

3. Kind and thickness of metal.

4. The portion of the frontal area which is open to allow the passage of air through the core, called "free area of the air tubes."

5. Extent and nature of cooling surface.

As an example of the way in which these factors influence the performance of the core, the following may be noted. As the depth of a core is increased the effectiveness of the cooling surface decreases owing to the rise in the temperature of the air as it passes through the air tubes, and the consequent decrease in temperature difference between the surface and the air. At the same time the amount of air that will flow through a tube decreases as the depth increases, tending further to reduce the cooling per unit surface. On the other hand, the total amount of cooling surface per unit of frontal area is increased, and at a much smaller cost in head resistance than would be the case if the frontal area were increased. Many of the effects of structural characteristics are governed by well-established laws so that a mathematical theory can be developed to predict their magnitude.

PROPERTIES EXPRESSING THE BEHAVIOR OF A CORE.

The properties of a core which express its performance are the following:

1. *Energy dissipated* (heat transfer or cooling capacity).—Since heat may be expressed in units of work, the rate of dissipation of heat may be expressed in units of power. It has been expressed in horsepower per square foot of frontal area, at any given air speed, for the con-

ditions of turbulent water flow and a temperature difference of 100° F. between the water and air, as defined below.

2. *Weight* of the core, and of the water contained, are important properties, being directly involved in the computation of horsepower absorbed.

3. *Head resistance of the core*, the force required to push it through the air, must be distinguished from head resistance *chargeable to the radiator* (defined above), which is the part of the over-all resistance of the plane caused by the radiator and any modifications of structure that the radiator may make necessary.

4. *Mass flow constant.*—It is found for all ordinary types of core that, when supported in a free air stream, the amount of air that passes through the core is proportional to the free air speed (at constant density), and therefore is proportional to the mass of air that would pass through the area occupied by the core if the core were removed. The fractional part of the air approaching the core, which actually passes through its air tubes, has been called the mass flow constant of the core. It is an important property, since the heat transfer and the head resistance are both closely related to it.

5. The *power absorbed* by a core may be computed from the head resistance and the weight as follows:

(a) If the total weight and the total available power (at the propeller) are known for the plane, the power absorbed by the weight of the core can be found approximately, and to this must be added the power required to overcome the head resistance, the latter being obtained directly from the head resistance and the speed of the plane.

(b) If the lift-drift ratio of the plane is known, it is simpler to divide the weight by this ratio, and thus reduce it to equivalent head resistance; i. e., drag on the wings and structure required to carry the weight, and to add this to the head resistance before multiplying by the plane speed to obtain the power absorbed.

In either case, it should be borne in mind that the power so computed is not necessarily equal to the power chargeable to the radiator, but is subject to the same limitations as the head resistance, as noted above. This method, which is intended to give a basis for comparison between cores, gives only an approximation. The British have shown by a very careful analysis the effect on a plane of small additions of weight and resistance, and it is shown that their relative importance varies greatly, according as top speed or rate of climb is given greater weight. This, of course, is due to the change in lift-drift ratio under various conditions.

6. *Figure of merit.*—In order to obtain a quantity by means of which the performance of various cores can easily be compared, it is necessary to consider both the energy dissipated and the power absorbed. The rate at which a radiator dissipates heat per unit power absorbed is a measure of the suitability of the radiator for airplane use so far as these two factors are concerned. This quantity has been called the figure of merit. The figure of merit will be the criterion for a radiator in any position, provided the power absorbed is the total power absorbed chargeable to the radiator as defined above. Unfortunately it is necessary to limit the definitions of head resistance *of a core* and power absorbed *by a core* to very specific conditions of use which can be accurately reproduced in the laboratory, so that it is only when the air flow around the radiator is not obstructed by other parts of the plane that the figure of merit *of a core* is of value in determining the figure of merit *of a radiator*.

CONDITIONS OF USE.

The conditions of use which affect the performance of the radiator, have been chosen not only to give the most accurate description of the factors which really determine the properties, but also to allow of easy comparison with the conditions found in flight. They are the following:

1. The *mass flow of air* through the core. This is defined as the mass of air that flows per second through the air tubes of a section of core of one square foot frontal area. This use of the term "mass flow" is identical with the common use of the term in the works of Osborne Reynolds and others, if the radiator is regarded as a structure through which air flows, and no account is taken of the fact that the flow is made up of a flow through a number of small tubes.

A careful distinction is made between the velocity of the air approaching the radiator (free air speed) and the mass flow through the core. It is the latter quantity that determines the effect of air velocity on heat transfer. It should be noted that the flow of air through the core depends upon many factors besides the free air speed.

2. *Temperature difference* between air and water. Strictly speaking, the heat transfer is determined by the mean over the entire core, of the temperature difference between the air and the water, at each small element of cooling surface. It can be shown, however, that for a given radiator under constant conditions of air flow and water flow, except that the air and water temperatures vary, the heat transfer is very nearly proportional to the difference between the mean temperature of the water and the temperature of the entering air. The water temperature depends, however, on the total length of the core, as well as upon the rate of flow through the core, so that it is much simpler to use the mean water temperature. The logarithmic mean should theoretically be used, but as the arithmetic mean differs from it very slightly under ordinary conditions of use it has been employed to save labor. The temperature difference under which a core works is given, then, as the difference between the temperature of the entering air and the mean of the temperatures of the entering and leaving water.

3. *Air density.*—Results have been reduced to a "standard" air density of 0.0750 pounds per cubic foot (0.001201 grams per cc; approximately density of dry air at 20° C., 78° F.).

4. *Flow of water* may be expressed in two ways, in quantity units, and in linear velocity through the tubes. The quantity of water flowing affects the drop in temperature of the water in passing through the radiator, while the linear velocity determines to some extent the rate of heat transfer.

5. The *mechanical condition of the air and water* in the tubes of the core is of considerable importance in determining its performance. If there is turbulent flow, the heat transfer will be by convection and can be much more rapid than in the case of streamline flow. On the other hand it is necessary to impart considerable energy to a fluid in order to produce turbulence, and this means an increased absorption of power by the radiator.

GENERALIZATION OF THE PROPERTIES OF A CORE TO OBTAIN THOSE OF A COMPLETE RADIATOR.

In considering the relations between the conditions under which a section of core operates when in a complete radiator, and the test conditions used in the laboratory, there are seen to be two general classes of locations in which a radiator may be placed on a plane. When the air flow around and through the radiator is not affected by the surrounding portions of the plane, the radiator is said to be in an *unobstructed position*. In this case there is no reciprocal effect of the radiator on the other parts of the plane, and the properties of a radiator in such a position may be computed from the results of laboratory tests.

When the air flow through the radiator is affected by other parts of the plane, it is said to be in an *obstructed position*. Such a radiator has a marked effect on the properties of surrounding portions of the plane, and the effects chargeable to it are not related in a simple manner to the properties of its core.

In order to obtain the properties of a radiator when in place from the properties of the core as determined by laboratory tests, it is necessary to know (1) the conditions of use of each part of the core, i. e., air flow, water flow, and temperatures; (2) the effect of headers, piping, etc.; and (3) the reciprocal effect of the radiator (especially the air flow through it) on other parts of the plane.

AIR FLOW THROUGH THE RADIATOR.

The mass flow of air through a radiator in an unobstructed position may be obtained directly from the mass flow constant of the core, the free air speed to which the core is subjected, and the air density. The free-air speed will usually be the plane speed, augmented by any effect of the propeller-slip stream. For a radiator in an obstructed position, the mass

flow of air can not easily be computed. It is hoped to make measurements of this mass flow in obstructed positions in a series of tests in flight.

TEMPERATURE DIFFERENCE.

As noted above, the temperature difference selected for expressing the energy dissipated was so chosen that the results can be applied at once to a radiator of any size by using the mean temperature of the water. The latter may be found from the entering temperature, the amount of heat to be dissipated, and the water flow. It is therefore possible to regard an entire radiator as having a mean temperature, and as the air entering all parts of the radiator will commonly have the same temperature, the mean temperature difference for the radiator is easily found.

FLOW OF WATER.

The linear velocity of the water in the tubes determines the turbulent condition of the flow and should be kept above a certain value for each type of core. The total quantity of water flowing per unit time determines the temperature drop in the water, and thus affects the temperature difference.

ENERGY DISSIPATED.

The laboratory tests of a core will give the energy dissipated under "standard" conditions for a unit frontal area of core, and for any mass flow. If the mass flow is known, the total heat dissipated will be found from the test results and the frontal area of the core. Conversely, if the heat to be dissipated is known, the required frontal area of core can be determined. The amount of heat to be dissipated is a subject that will bear some study under actual flight conditions. In particular, the effect of the air that passes through a nose radiator, in cooling directly the walls of the engine jackets, should be determined, for it is an effect with which the radiator (or the position) should be credited.

HEAD RESISTANCE.

The head resistance of a radiator placed in an unobstructed position may be obtained directly from that of the core. It is roughly proportional to the frontal area, but includes the effect of headers and connections. For an obstructed position, if the mass flow of air is known, the head resistance *of the core* will be the same as that given in an unobstructed position when at such a speed as gives the same mass flow. But this value represents only that part of the total resistance chargeable to the radiator which is due to the pressure difference on its two faces. The resistance which other parts of the plane offer to the air which has passed through the radiator may be very considerable. Also, if the front of the fuselage has to be enlarged in order to accommodate a large nose radiator, this may cause a very great increase in the resistance of the fuselage, all of which is chargeable to the radiator. The resistance of obstructed radiators requires special study.

POWER ABSORBED.

The power absorbed by an unobstructed radiator may be obtained from that of the core as given, by a laboratory test with corrections for headers and connections. Since, however, it depends upon the lift-drift ratio of the plane (it has been computed for a ratio of 5.4), a special computation using the actual lift-drift ratio of the plane will give a better value. The values given with the results of tests are intended chiefly for comparative purposes. In obstructed positions the power absorbed must be specially determined.

FIGURE OF MERIT.

The figure of merit of a radiator in an unobstructed position will for comparative purposes be equal to that of the core. For obstructed positions it must be specially computed. It will always be less than that of the same radiator in an unobstructed position with the same mass flow of air.

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REPORT No. 60

GENERAL DISCUSSION OF TEST METHODS FOR RADIATORS

BY

H. C. DICKINSON, W. S. JAMES, AND W. B. BROWN

Bureau of Standards, Washington, D. C.

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REPORT No. 60.

GENERAL DISCUSSION OF TEST METHODS FOR RADIATORS.

By H. C. Dickinson, W. S. James, and W. B. Brown.

INTRODUCTION.

It has been shown in the analysis of the airplane radiator problem that it is necessary to make measurements on—

(1) The core characteristics which define its nature.
(2) Heat dissipated, as dependent on—
  (*a*) Nature of core.
  (*b*) Mass flow of air through the core.
  (*c*) Density of the air.
  (*d*) Water flow through the core.
  (*e*) Temperature difference between the air and water.
(3) Power needed to lift the radiator and overcome its head resistance, as dependent on—
  (*a*) Nature of core.
  (*b*) Air speed in the open.
  (*c*) Air density.
(4) Mass flow of air through the core, as dependent on—
  (*a*) Nature of the core.
  (*b*) Air speed in the open.
(5) Power needed to circulate water through the core, as dependent on—
  (*a*) Nature of the core.
  (*b*) Rate of water flow.

Point (5) has been covered by Report No. 63, Part II, and is entirely distinct from the others. The following paragraphs describe (*a*) the apparatus, (*b*) the method of taking observations, (*c*) the method of computing the results, for the first four.

Test Specimens.

The specimens tested for head resistance were plain sections of core without water boxes or other attachments. They varied in size from approximately 6 inches square to approximately 12 inches by 24 inches and 16 inches square.

Those tested for rate of heat dissipation were uniform in size and fittings. The cores were 8 inches square, with water boxes 1 inch deep, as shown in Fig. 1. The entrance and exit water pipes were fitted onto brass tubing 1½ inches deep and 1½ inches in diameter, which were inserted into each water box. Just inside the water box was a baffle of brass to equalize the water flow through the core.

(1) CORE CHARACTERISTICS.

The core charcteristics determined were:

(1) Dimensions of the water tubes, length (parallel to the direction of water flow), depth (parallel to the direction of air flow), thickness (perpendicular to previous two), hydraulic radius (ratio of area of a section perpendicular to the direction of water flow to its perimeter).

(2) Dimensions of air tubes, depth (same direction as depth above), and hydraulic radius.

(3) Per cent free area of air passages.
(4) Extent and distribution of the cooling surface.
(5) Weight of the core empty and filled with water.
(6) Nature and thickness of the metal.
(7) Shape of the air and water passages.

DIMENSIONS OF THE WATER TUBES.

The apparatus used to measure the cross section of the water tubes is shown in figure 2. A radiator specimen, R, with water tubes t–t, was placed upright on a support. Water from a graduated burette B was admitted into the radiator until the water level was a little way above the entrance to the water tubes. Suppose this level was h_2. This and the water level in the burette B were read. The cock C was opened and water admitted to the radiator until another level h was reached, when readings of the gauge and burette were taken again. When from 6 to 10 different levels had been observed and a level h_1, near the top of the specimen reached, the burette was moved to position 1 and readings taken while emptying the radiator.

The burette B was calibrated by weighing its water content at different levels. The fine dividing engine of the Division of Weights and Measures was used to calibrate the gauge. This was read (while taking observations) to 0.01 cm. and the volume to 1 cc.

Volumes in cc. were plotted against gauge levels in cm. and the points found to lie on a straight line. If the slope of this line is denoted by m, the area of the water tubes by a, and the area of the gauge by g, then since all the water leaving the burette goes into the radiator and gauge and raises the level of each by the same amount,

$$m = a + g \tag{1}$$

The constant g was determined previously by using in the gauge known volumes of water.

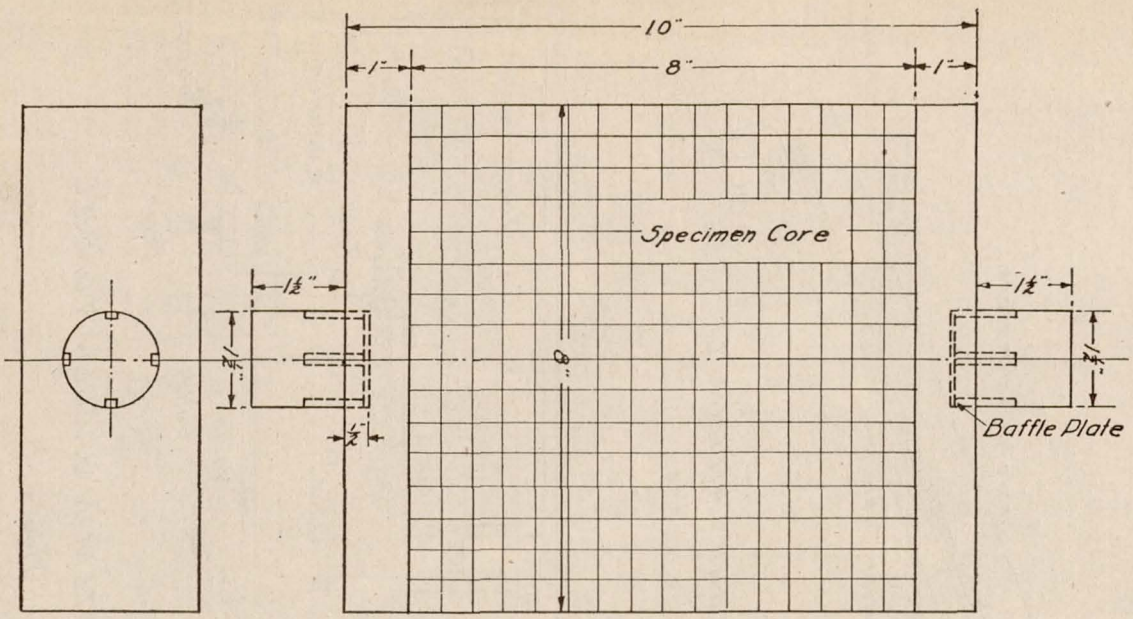
Two tests were made on each specimen. If the resulting values of a differed more than 3 per cent, other tests were made. The number of water tubes was counted. The depth of the tubes was measured with a rule and calipers. When the water tubes were not vertical, e. g., in the hexagonal cell types, the area above (which is, of course, the horizontal area) was projected onto a plane normal to the direction of the water flow. This projected area divided by the number of tubes gave the area of one tube. A further division by the depth gave the thickness. Twice the sum of the thickness and depth is the perimeter, and this divided into area gave the hydraulic radius. The water-tube length in inches of a foot square section is $12/F$, if F is the above projection factor.

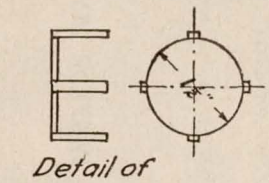
a was expressed in square feet per foot of core width, so that the water content of the core was 62.4 a, 62.4 being the density of water in pounds per cubic foot.

DIMENSIONS OF THE AIR TUBES.

The method used in finding the cross sectional area of the air tubes was similar to the one just described. The specimen was clamped face down onto the top of a shallow tank 7 inches square and 2 inches deep. The rim of the tank was 1 inch broad and was faced with a strip of soft rubber, so that the edge of the specimen was sealed water-tight. The tank contained two openings to which rubber tubes could be attached, one leading to the burette and the other to the gauge as before.

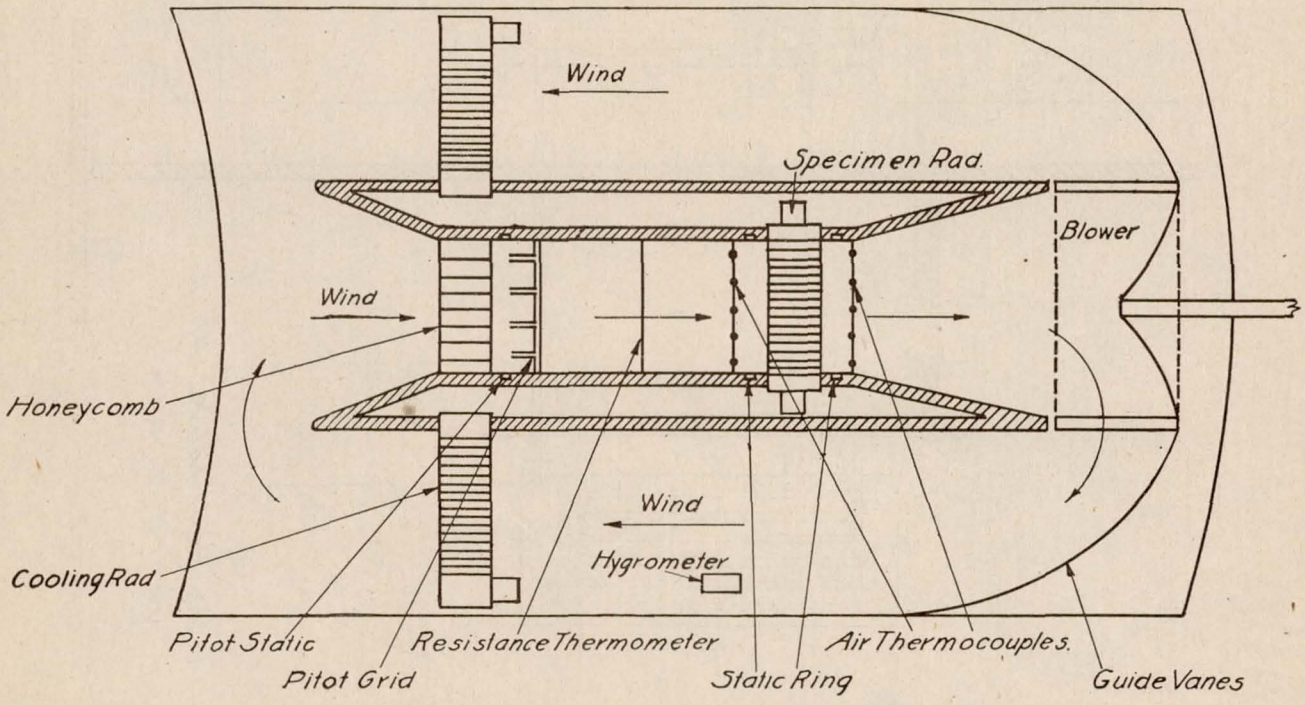
The observations and computations were exactly the same as in the case of the water tubes. Micrometer measurements on the inside of the air tubes and a direct count of their number determined the perimeter of the air tubes, and when combined with the area above, the hydraulic





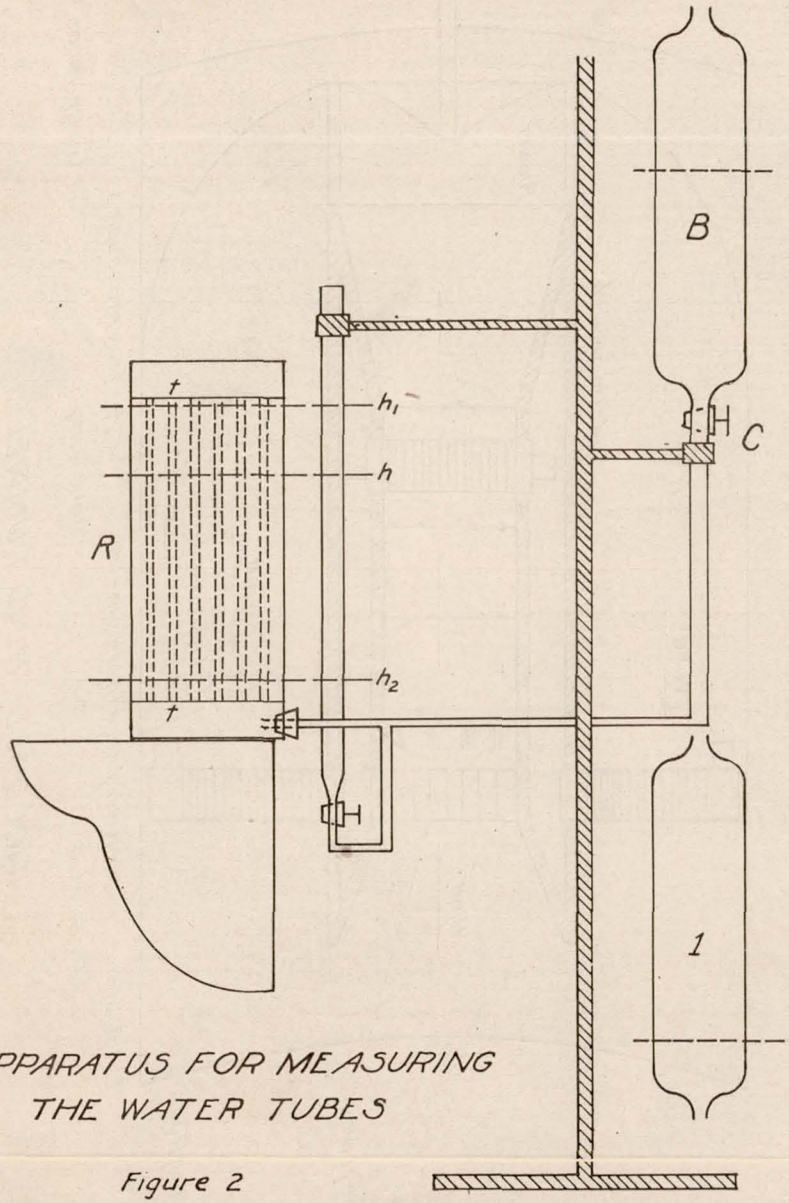
RADIATOR INVESTIGATION
TEST SPECIMEN

Figure 1



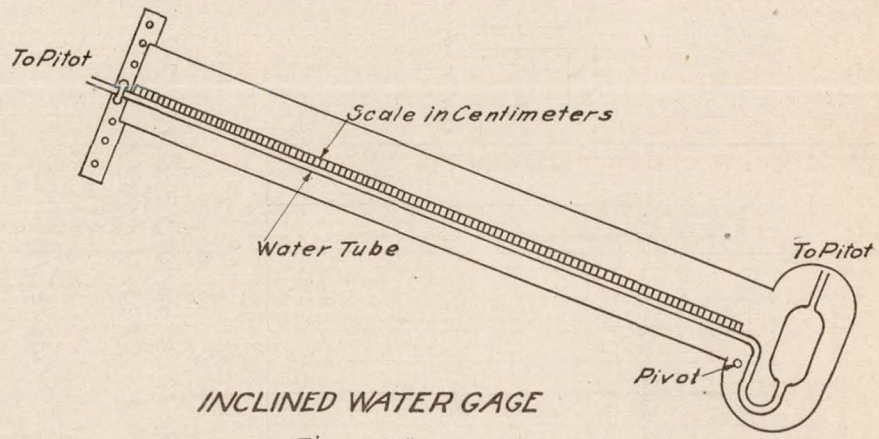
INCLOSED WIND TUNNEL

Figure 3



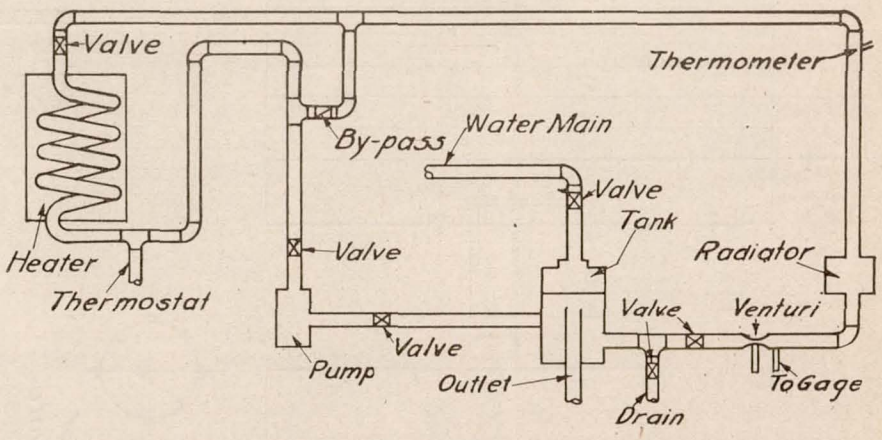
APPARATUS FOR MEASURING THE WATER TUBES

Figure 2



INCLINED WATER GAGE

Figure 4



WATER SYSTEM IN VACUUM TUNNEL

Figure 5

radius also. These observations gave an independent value of the air-tube area which agreed well with the results of the above method.

The air-tube depth (identical with the core depth) was measured with a rule and calipers.

FREE AREA OF THE AIR PASSAGES.

Since the specimens were seldom exactly 8 inches square, careful measurements of the true frontal area were made and divided into the air-tube area to give the per cent of free area.

EXTENT AND DISTRIBUTION OF THE COOLING SURFACE.

When the air tubes had a simple shape, circular, hexagonal, rectangular, etc., so that the relation between the area and the perimeter was known, the air-tube measurements above sufficed to determine the cooling surface, since this is the product of the perimeter of a tube by the number of tubes by the core depth. (Note: A slight correction had to be made sometimes on account of the enlargement at the edges.) Inspection of the radiator construction showed what portion of the surface was direct, i. e., formed part of a water tube or water box wall, and what indirect, i. e., received heat from the water only by conduction along a metal fin of some sort. (E. g., in a Harrison hexagonal cell type, two sides of each air cell formed part of a water tube. Hence one-third of this part of the core was rated as direct surface and two-thirds as indirect.) The edges were all rated indirect.

With the irregular shapes, many different methods of solution were used, depending on the nature of the irregularity. Every effort was made to determine these values to 2 per cent, but in a few cases the values could not be fixed with certainty to better than 10 per cent. Two observers worked independently and compared their results, so that large errors were not apt to escape detection.

WEIGHT OF THE CORE.

The weight of the core empty was found by weighing it with the water boxes removed on a balance. The water content added to this gave the weight of the core filled.

NATURE AND THICKNESS OF THE METAL.

All the specimens tested were made of copper or brass, as determined by inspection. The metal thickness was measured with a stage micrometer reading to 0.005 mm. The readings however, were not very uniform, so the values obtained are not accurate to that degree, e. g., two readings would give 0.008 and 0.010 mm.

SHAPE OF THE AIR AND WATER PASSAGES.

This was determined by inspection and some rough measurements and sketched on the curve sheets.

(2) HEAT DISSIPATED.

Two distinct sets of measurements were made on the heat dissipated and two different sets of apparatus used. Both made use of 8-inch square wind tunnels and were made so that the same specimen could be tested in both tunnels without any alterations. One tunnel was inclosed in a tank which could be partially exhausted and used hot water to supply heat to the radiator. The other was an open tunnel in the room and supplied heat by means of steam.

APPARATUS IN THE INCLOSED TUNNEL.

A diagrammatic sketch of this tunnel is shown in figure 3. Air flow was produced by the suction of a 15-inch Sirocco fan driven by a belt from a 220-volt, direct-current shunt motor, rated at 7½ horsepower; 110-volt current could also be used. A further adjustment afforded by rheostats in both field and armature enabled any speed through the tunnel between 15 and 60 miles per hour to be obtained. Both the fan and the tunnel proper were inclosed in a steel

tank 5 feet long and 3 feet in diameter. This was sufficiently air tight to allow the maintenance within it of a pressure of 30 or 40 cm. of Hg.

At the tunnel entrance a honeycomb of sheet-metal cells, 1 inch square and 3 inches deep, served to break up vortices and straighten the air flow. Following this in order came:

(1) A Pitot grid to measure the air speed.
(2) A resistance thermometer to measure the air temperature.
(3) A thermocouple grid to measure the rise in the air temperature as it passed through the radiator.
(4) A piezometer ring to measure the drop in the static pressure of the air.
(5) The specimen under test.
(6) The other piezometer ring.
(7) The other thermocouple grid.
(8) The fan.
(9) Conical guide vanes to deflect the air down the tank.
(10) A wet and dry bulb hygrometer to measure the humidity.
(11) A cold-water radiator to cool the heated air.

Water flow was produced by a centrifugal pump driven by a belt from a one-horsepower direct-current shunt motor. The water line is sketched in figure 5. The resistance of the heating coils to the water flow was quite large compared with the rest of the line, so that high rates of water flow (above 11 gals./min.) could only be obtained by opening the by-pass around the heater. A thermostat maintained a constant temperature at the radiator inlet. After the heater followed in order:

(1) A Hg. thermometer to regulate the thermostat.
(2) A set of thermocouples to measure the temperature drop in the water.
(3) The specimen under test.
(4) The other half of the thermocouple set.
(5) A Venturi meter to measure the water flow.
(6) A drain.
(7) A tank with a free water surface to open the system.

Construction and calibration of the apparatus: The air-flow measurement offered some difficulty. A Thomas meter was first used for the purpose, but owing to the high air speed and very irregular velocity distribution, it proved very unsatisfactory and had to be discarded. In its place was installed the Pitot grid. This contained 16 dynamic openings, one at the center of each 2 inch square section of the tunnel. All these opened into one tube leading to one arm of an inclined water gauge. A piezometer ring measured the static pressure and led to the other side of the gauge. A piece of sheet copper was carefully inlaid in the tunnel for a distance of $6\frac{3}{4}$ inches, so that the air passed over a very smooth surface before reaching the piezometer ring. Four square copper tubes were soldered onto the back of this ring $4\frac{3}{4}$ inches from its entrance, at the point of the dynamic openings. At $\frac{1}{2}$-inch intervals all around this, holes $\frac{1}{2}$ mm. in diameter were drilled. The burr was carefully scraped off the holes, and then the holes were cleaned out and smoothed with a hand drill.

One of the inclined water gauges is shown in figure 4. These were calibrated in each position by connecting them in parallel with a V tube containing light oil of a known density. A zero reading (scale reading with zero pressure difference) was taken before and after a run. Both the zero and the calibration remained sensibly constant over a period of many weeks.

A careful exploration of the channel at various speeds over the range obtainable was made with a standard Pitot. This Pitot was moved about at 49 different points spaced regularly over the channel and the velocity as indicated by it and the grid read. Observations were also made on the pressure difference between the static opening on this Pitot and the piezometer

ring. This last varied slightly around zero, showing that the static pressure was constant across the channel within 3 per cent of the velocity head sought. When the velocity was integrated over the channel it was found to agree within 1½ per cent with the velocity indicated by the Pitot grid at all speeds.

A barometer was connected with this piezometer ring so as to read directly the air pressure at the Pitot.

The resistance thermometer was made in the form shown in figure 6. No. 40 nickel wire was used, inclosed in a 0.5 mm. copper tube. This wire was calibrated by the thermometer section of the bureau and found to satisfy the following equation:

$$R = 103.367\ (1 + .003414\ t. + .00000419\ t^2). \tag{2}$$

When R = resistance of the wire in ohms.

t = temperature of the wire in °C.

The bridge used to read R was calibrated by the Electrical Division of the bureau and the corrections found to be negligible. A rough calculation showed that the maximum error caused by neglecting the lead resistance amounted to °.15 C. This produced an error of −0.2 per cent in the result.

At first an attempt was made to measure the temperature rise in the air through the Thomas meter and through the radiator with 200 ohm resistance thermometers in which insulated nickel wire was strung on a lattice work of iron wire. Owing to the varying stresses on the wire caused by the air stream, the resistance changed so much as to vitiate the measurements of small temperature differences (about 1° C.).

The thermocouple grids proved much more satisfactory. They each consisted of 25 copper-constantan junctions spaced at equal intervals over the channel.

Calibration showed that they satisfied the following equation:

$$\frac{de}{dt} = .933 + .0022\ t \tag{3}$$

or

$$e = .933 + .0011\ t^2 \tag{4}$$

where e = E. M. F. in millivolts when cold junctions were at 0° C. This E. M. F. was measured by means of a Morris E. Leeds' 15,000-ohm potentiometer, sensitive to 10 microvolts.

The static rings about the radiator were constructed exactly like the piezometer ring described above, save that the copper ring was 2 inches long.

The Venturi was connected to a mercury pressure gauge and the whole contrivance calibrated by weighing the water discharged through it in a known time.

A 10-foot gravity head was originally used instead of the pressure of the pump to produce the water flow through the radiator, but this was discarded because it did not give sufficiently high rates of flow. The pipes were insulated with magnesia pipe lagging 1 inch thick.

Many methods of arranging the thermocouples so as to measure accurately the temperature drop in the water were tried before a successful one was found. A single couple in the inlet and outlet pipe proved too erratic. Four couples in series in the center of the box itself failed to give a good temperature integration besides giving such a small reading that it was much affected by small thermal E. M. F.'s in the line. Twenty-one couples arranged in three groups of seven each, one in the center of the water box and one on each side, gave very good readings and a good temperature integration but proved too fragile to withstand the hard usage received in changing specimens.

Finally 21 couples, about one-half inch apart, were incased in a copper tube in the form of a spiral coil and placed in the inlet and outlet water pipes. These proved very successful in every respect.

They measured only the temperature drop in the water. To measure the absolute temperature of the water, an extra constantan lead from the first junction ran to a cold junction placed in an oil bath outside the tank (see fig. 7). The temperature of this bath was measured by a mercury thermometer graduated to 0.1° C., which had been calibrated by the thermometer section of the bureau.

The single couple just referred to and the 21 couples in series were calibrated separately and found to satisfy the following equations respectively:

(5) $$e = 39.10t + .04t^2$$

(6) $$e = 39.97t + .0314t^2$$

e is here expressed in microvolts per couple, t in degrees C.

Method of observing.—The machinery was first set in motion and allowed to run until the temperature conditions became steady. Two observers worked simultaneously, one reading the electrical instruments that measured the temperatures, the other reading the pressure gauges and the hygrometer. The sample observation sheets, figures 8 and 9, give such a set. The time of each observation was recorded in small figures above it.

After complete readings had been taken under one set of conditions, one of them was changed and another set of readings taken. A complete set of observations on one specimen included sets under atmospheric conditions with constant water flow and varying air speeds; with constant water and air flow, but varying air speeds and pressures; with different constant air speeds, but varying water flow. A special set was taken on one specimen under atmospheric conditions with constant air and water flow, but with varying inlet water temperatures.

Method of computing results.—The given data, figure 10, sufficed to determine:

(1) Pressure drop in the air through the radiator lb.-wt./ft.^{2}

(2) Rate of water flow in gal./min./ft. width of core and speed in ft./min.

(3) Rate of air flow in lb./sec./ft.^{2} frontal core area.

(4) Air density in lb./ft.^{3}

(5) Heat given up by the water in horsepower per 100° F. difference between mean temperature of water and entrance temperature of the air per square foot frontal area of core.

(6) Heat received by the air in same units.

These results were used to plot the following curves:

	Ordinate.	Abscissa.	Constant.	Constant.
(a)	(5)	(3)	(2)	(4)
(b)	(6)	(3)	(2)	(4)
(c)	(6)	(2)	(3)	(4)
(d)	(6)	(4)	(2)	(3)
(e)	(1)	(3)	(4)	
(f)	(1)	(4)	(3)	

The computation sheet (fig. 10) exhibits the details of the computation. The explanation follows:

Pressure drop.—This equals a conversion factor × gauge reading.

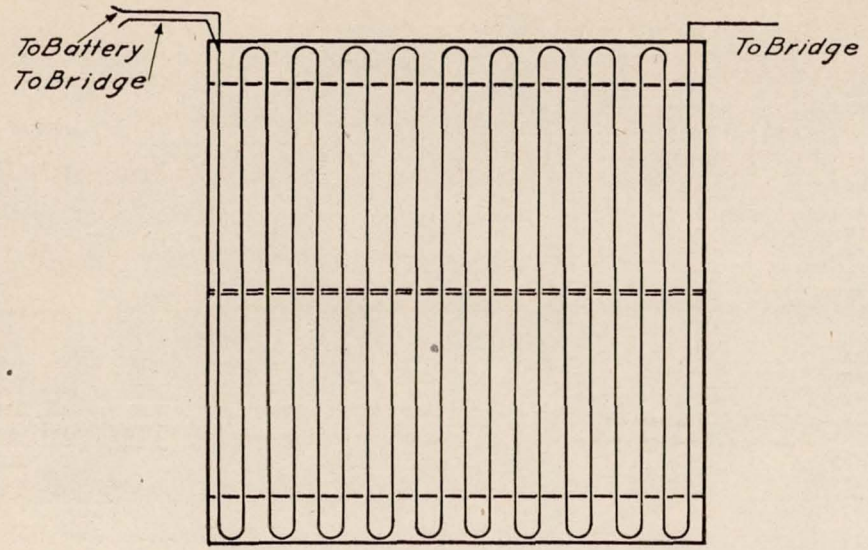
Water flow.—Let H = Venturi reading

W = water flow in gals./min./ft.

V = water speed in ft./min.

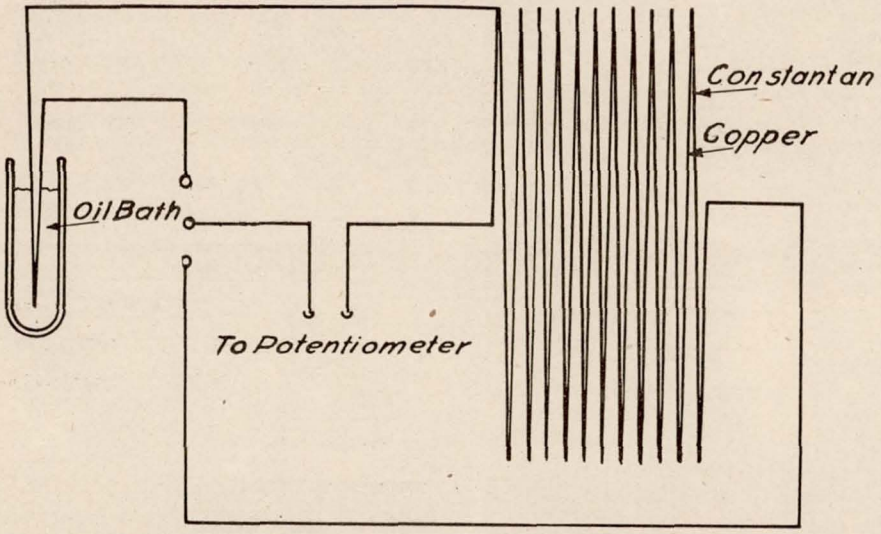
S = water density in g./cc.

A = water tube area in cm.^{2}



RESISTANCE THERMOMETER

Figure 6



WATER THERMOCOUPLES

Figure 7.

DATA SHEET

VACUUM TUNNEL LABORATORY

BUREAU OF STANDARDS

* Temperature Readings *

Run No. 716

Observer L. E. V. Water thermocouple # 3V

Time	Resistance thermometer Ohms	Air inlet & outlet mv	Water inlet & outside mv	Water inlet & outlet mv	Temperature water inlet C	Temperature cold junction thermocouple C
	01 m			1		
4h	116.46			1970		
		2		2		
		16950		1920		
			4 2760	4 1920		4 32.80
			4 2760	5 1920		4 32.80
		6		6		
		17080		1930		
	7					
4h	116.33					

Remarks :

Figure 8

15215—S. Doc. 166, 66-2——16

DATA SHEET

VACUUM TUNNEL LABORATORY

BUREAU OF STANDARDS

* Gage Readings *

Run No. 716 — Section # 45

Mc Cord Radiator — Date 6-20-18

Observer W.N.H. — Motor R.P.M. 750

Time		Venturi (cm Hg)	Temp Vent C	Press. Drop cm	Temp. P.D.gage C	Pitot cm	Temp pitot C	Hygrometer Wet C	Hygrometer Dry C	Barometer Hg cm	Barometer temp C
	Left		2m							Left 67.10	
4h	Right	38.0	29.5	18.18	30.5	8.79	30.5			Right 27.25	31.5
	Left									Left 67.08	(6)
	Right	38.1		18.21		8.73		38.1	56.9	Right 27.27	
	Left									Left 67.01	(7)
	Right	38.0		17.78		8.53				Right 27.31	
	Left									Left	
	Right									Right	
	Left									Diff. ~~Left~~ 39.85	
	Right									" ~~Right~~ 39.81	
										" 39.70	
	Left									Left	
	Right									Right	
	Left									Left	
	Right									Right	
mean	~~Left~~	38.03		18.05		8.70				mean ~~Left~~ 397.9	mm
zero	~~Right~~	27.53		2.45		4.55				corr. ~~Right~~ -2.6	
True height		10.50		15.60		4.15				True bar. 395	

Remarks :

Figure 9

COMPUTATION SHEET FOR VACUUM TUNNEL

* * * * BUREAU OF STANDARDS * * * *

Mc Cord Radiator — Section # 45

Calculator W.B.B. — Observers L.E.V. W.N.H.

Run No.	714	715	716
Date 1918	6-20	—	—
Time	3h30m	3h50m	4h04m
Wet bulb C	—	41.0	38.1
Dry bulb C	—	56.0	56.9
T		.08	.10
76 - P cm. Hg.		27	36
Correction to % humidity		2	4
Apparent % humidity		41	32
% humidity		43	36
Temp. air at entrance C	34.9	35.1	35.4
Mean temp. water C	35.1	34.7	34.2
Pressure mm. Hg	593	493	395
Density of dry air lb/ft^3	.0558	.0464	.0371
Humidity correction "	.0017	.0017	.0016
Density of air "	.0541	.0447	.0355
Pitot constant	3.94	3.94	3.94
Pitot reading	2.76	3.14	4.15
Air flow lb/sec/ft^2	1.52	1.48	1.51
Air temp. rise mv.	17140	17400	17015
Air temp. rise C	16.67	16.91	16.52
Temp. cold junction mv	1377	1300	1326
Water inlet temp. mv	2805	2805	2760
-1/42 water couple mv	+46	45	46
Mean water temp. mv	4081	4060	4040
K	1387	1388	1389
Water couple mv	1944	1908	1932
Mean water - entrance air C	60.2	53.6	58.8
Venturi gage cm. Hg	10.37	10.47	10.50
Heat lost by water HP/ft^2/100 F	14.41	14.36	14.78
Heat received by air " "	14.65	14.61	14.75
Water velocity constant	24.8	24.8	24.8
Water velocity ft/min	80.0	80.4	80.5
Water flow gal/min/ft	15.08	15.15	15.17
Air pressure drop lb/ft^3	4.25	4.90	6.47

Remarks:

Figure 10

then the Venturi formula gives—

(7) $$W = 4.69\ \sqrt{HS}$$

(8) $$V = 386.2\sqrt{\frac{FH}{a^2}}$$

where 4.69 is a factor found by calibration, F is a factor found by calibration to reduce gauge readings to cm. Hg., its value being 1.008. 386.2 is a computed conversion factor.

All the gauges had temperature coefficients, but these gave rise to negligible corrections over the annual temperature range of the room.

Air density.—Let P = air pressure at the Pitot in mm. Hg.

t = air temperature at the Pitot in °C.

d^1 = density dry air at the Pitot in lbs./ft.^{3}

then the gas laws as applied to air gave

(9) $$d^1 = \frac{.029P}{t+273}$$

In addition let d = true density of air in lb./ft.^{3} and $d = d^1 + C$.

It follows from the laws for mixtures of gases and vapors that

(10) $$C = R\left(S_2 - \frac{.029\ e_2}{t+273}\right)$$

Wherein R = relative humidity.

S_2 = density of saturated water vapor at t°C in lb./ft.^{3}

and e_2 = pressure of saturated water vapor at t°C in mm. Hg.

R was found from the wet and dry bulb readings by means of an ordinary chart for the purpose. In the case of the reduced pressure runs, the value found thus required a correction r derived from the formula of W. H. Carrier (A. S. M. E. Trans., 1911, pp. 1005 et seq).

(11) $$r = (76-P)\,T$$

(12) $$T = \frac{t-t^1}{(2803-1.33t)e_2}$$

if t and t^1 are dry and wet bulb temperatures, respectively, in °F. (This is the T appearing in the sixth line of the computation sheet.)

Air flow.—Let M = Air flow in lb./sec./ft.^{2}

h = reading on the Pitot gauge

A = Pitot constant

F_1 = factor to convert the reading to g./cm.^{2}

then the Pitot formula gives,

(13) $M = A\sqrt{hd}$ where $A = 11.49\sqrt{F_1}$. 11.49 is a conversion factor.

Heat received by the air.—Let

$\left(\frac{de}{dt}\right)_m$ = slope of e–t curve at mean temp. of air in radiator.

and De = E. M. F. between air inlet and outlet couples in millivolts.

Q_a = heat received by the air in H. P./ft.^{2}/100° F.

Dt = temperature rise in the air in °C.

C = specific heat of the air at constant pressure.

(13a) then $Dt = \left(\frac{De}{\frac{de}{dt}}\right)_m$ because (4) is a parabolic equation.

From the definition of Q_a it follows that

$$Q_a = \frac{141.4\ C_p\ .\ M\ .\ Dt}{t_w - t} \tag{14}$$

Wherein t_w = mean temperature of water in °C. and 141.4 is a conversion factor.
C_p = 0.246 according to W. C. Rowse (A. S. M. E. 1913), for 40° C. and 40 per cent humidity.

Heat lost by the water.—Let

e_o = the E. M. F. between 0° C. and the temp. of the oil bath (microvolts/couple)
De = the E. M. F. between oil bath temp. and that of inlet water.
De_w = the E. M. F. between water temp. at inlet and at outlet.
e_w = the E. M. F. between 0° C. and mean temp. of water.
Q_w = the heat lost by the water in H. P./ft.²/100° F.

If now in place of the E. M. F. corresponding to the mean water temperature is put the average E. M. F. of the couples in the water stream at the entrance and exit of the specimen there results

$$e_w = e_o + De - \frac{De_w}{42} \tag{15}$$

The error due to this substitution never exceeds 0.09° C. and was usually about 0.001° C. t_w was found by equation (5)

For this case there are two equations similar to (13a) and (14) for air. If for M in (14) is put its value as given by the Venturi equation (7), and for Dt its value as given by (13a), the result is:

$$Q_w = \frac{KDe_w\sqrt{H}}{t_w - t} \tag{16}$$

Where

$$K = K^1 + DK$$

and

$$K^1 = \frac{.701 \times 196.21 C_w \sqrt{F} S_w}{n\left(\frac{de}{dt}\right)_w}$$

and

$$DK = \frac{.0427 De_w \sqrt{F}}{n^2\left(\frac{de}{dt}\right)_w^2}$$

.701 converts *g.* cal./sec./deg. C/8-inch sq. frontal area to H. P./ft.²/100° F.
196.21 converts cm./Hg on the Venturi to cc./sec.
C_w = Specific heat of water at t_w° C.
S_w = density of water at t_w° C.
n = number of thermocouples (here 21).

DK is a small correction less than 0.5 per cent of K, which allowed for the fact that the Venturi was at the water outlet and hence S was greater than S_w by an amount proportional to Dt, the temperature drop in the water. In practice K^1 was tabulated as a function of t_w and abbreviated the computation.

APPARATUS IN THE STEAM TUNNEL.

The steam tunnel was open and not inclosed like the one just considered. A sketch of it is shown in figure 11. Air was pushed through the tunnel by a 36-inch Sturtevant Blower driven by a 220-volt direct current shunt motor rated at 10 horsepower. Adjustable rheostats in both field and armature gave a range of speeds from 30 to 100 miles per hour when the channel was unobstructed. By blocking up the air intake the speed was further reduced to 10 miles per hour. A mercury thermometer inserted through the tunnel wall measured the air tem

peratures to 0.°5 C. A Pitot grid and two piezometer rings were installed just as in the inclosed tunnel. In addition two other rings 7 inches from the radiator faces were used.

The barometer was in the room, so that observations had to be made on the pressure difference between the air in the tunnel and in the room. This was accomplished by opening the low-pressure side of the pressure drop gauge to the air in the room.

A recording hygrometer registered the humidity with sufficient accuracy.

The heat dissipated by the radiator was supplied by the condensation of dry steam. Figure 12 gives a sketch of the apparatus used to control and measure the steam flow. Steam from the high-pressure mains (100 lbs./in.^{2} was passed through a valve where its pressure was reduced to about 10 lbs./in.^{2}. A V-shaped pipe with an opening at the bottom drained out most of the water. The steam passed on through a coil where it was superheated about 50° C., through a plug cock where its pressure fell to atmospheric, through a separator where a mercury thermometer recorded its temperature, through the radiator specimen where most of it condensed and through another separator out of which the water dropped into a weighing tank.

Originally a thermometer was inserted in the lower water box of the specimen, but the water temperature was found to differ so slightly from the temperature of condensation that the heat lost by the water in cooling could be safely neglected. A fan blew the steam away from the tunnel. The steam line was insulated in the same manner as the water line in the other tunnel. The radiator specimen was insulated on the sides with cork board one-half inch thick. The water boxes were not so well protected, but on account of the small surface exposed and the comparatively quiet air in contact with them, the heat lost thus could not have been more than a few tenths of a per cent at moderate speeds. In fact, in some of the early experiments, the steam condensed when the channel was blocked so no air flow existed was measured and found to be less than 1 per cent of the total.

Method of observing.—The exhaust valves in the steam line were opened, the water drained off and the blower started. When the water was out of the line and the steam flowing well, the gas heater was lighted, and the blower adjusted to give the desired speed. After steady conditions of steam flow and temperature had been attained, one observer set the balance slightly ahead of the actual weight and started a stop-watch when the pointer crossed the zero line. The balance was set ahead of the weight (from 1 to 10 pounds, according to the probable rate of condensation), and one observer from then on recorded steam temperatures. At the same time the other observer read the gauges and the air temperature. A set of readings was taken at regular intervals (every one or two minutes, according to the duration of the run). About a minute before the assigned weight was reached, a bell warned the observers, who prepared to observe the time when the pointer crossed the line again. At each speed two or three runs were taken as a check. The time interval employed was from three to six minutes, and could easily be measured to 1 second. The balance weighed correctly to 0.01 pound. An observation sheet (fig. 13) is reproduced.

Method of computing results.—As in the case of the inclosed tunnel the observed data sufficed to determine—

(1) Pressure drop in the air through the radiator.
(2) Rate of air flow.
(3) Heat given up by the steam.

Pressure drop.—This result was computed as in the other tunnel with one addition. Because the piezometer rings were 7 inches from the radiator, (1) was corrected by subtracting from it the pressure drop in 14 inches of unobstructed channel.

Air flow.—The computation was the same as before.

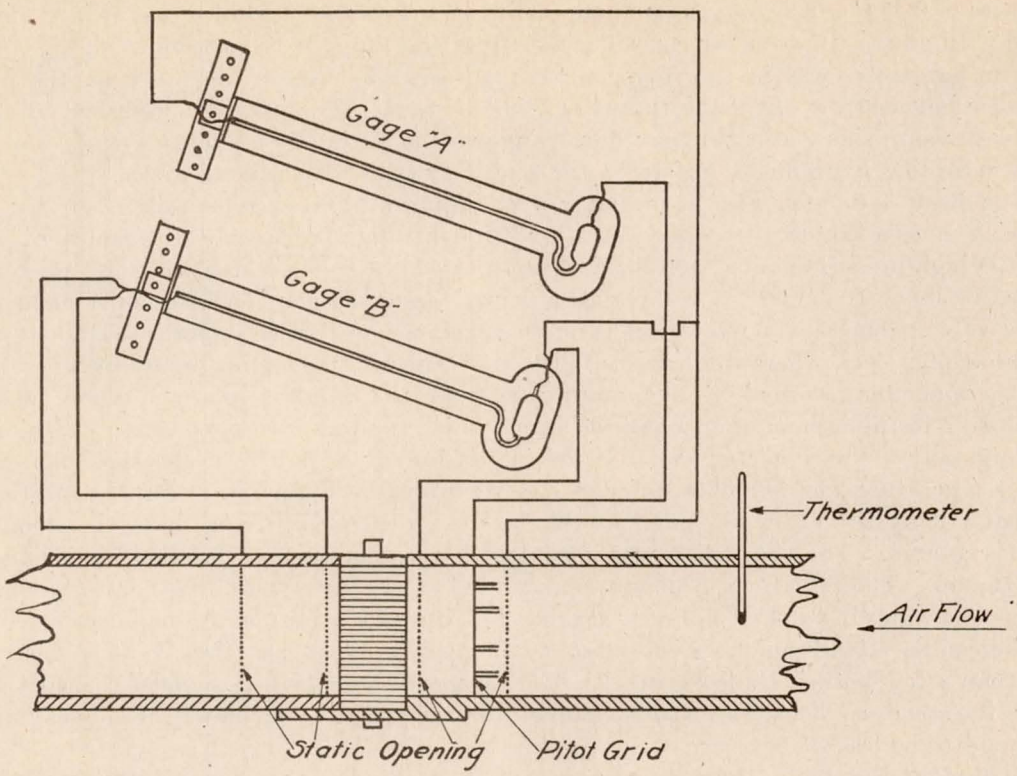


Figure 11

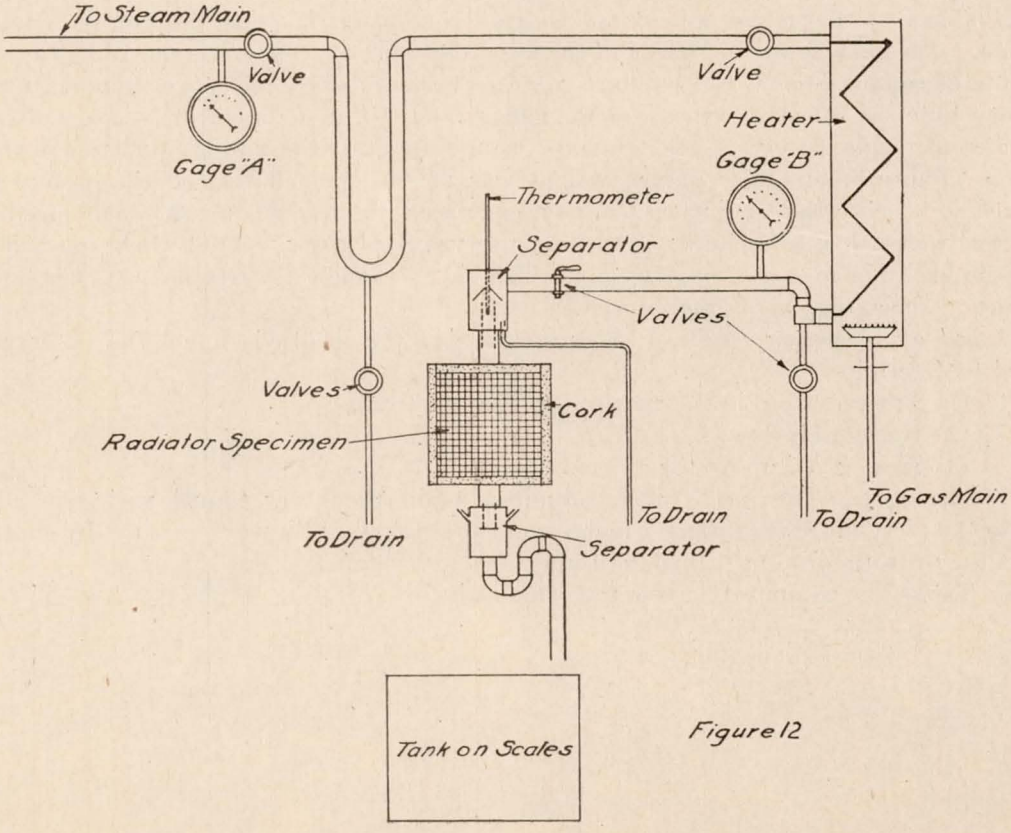


Figure 12

--- LOG SHEET ---

Steam Condensation Wind Channel

BUREAU OF STANDARDS

Run No 303a Date 6-11-18

Mc Cord Radiator Section # 45"

*Press. (A)	Gages (B)	Steam temp. (C)	Air veloc (cm)	Temp V. gage (C)	Press drop (cm)	Temp P.D. gage (C)	Temp. air Front (C)	Back (C)	
97	7.5	132.0	37.3		49.3		36.8		
100	7.5	132.0	37.4		49.2		37.2		
100	7.6	132.0	37.6		49.4		37.3		
mean		132.0	37.4		49.3		37.1		
zero			13.2		3.9				
True height			24.2		45.4				
Gage zeros			13.2		3.9				

Wt. water condensed 3 lbs. Time elapsed 4 min, 43 sec

Start 2h 51m 01s

Barometer 86.07 cm, temp 32.5 C. Time of run Finish 2 55 46

106.7 cm

75.40 cm Gage Settings, A 2, B 4,

Humidity 50 % Observers _____

Remarks : * These readings are not used in the computation. The observer uses them to maintain a steady steam flow.

Figure 13

Sheet No 1

COMPUTATION SHEET FOR STEAM TUNNEL

* * * BUREAU OF STANDARDS * * *

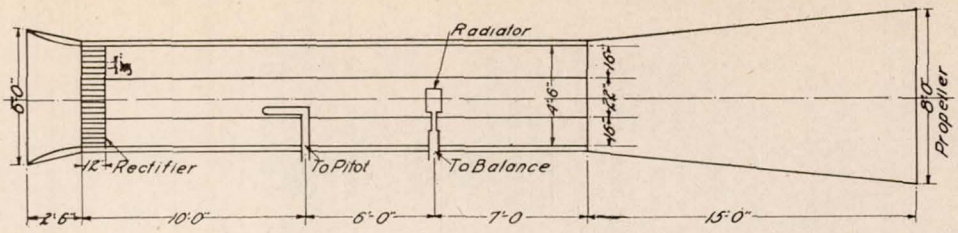
Mc Cord Radiator Section # 45 Size 3½ deep

Calculator R.A.C. E.S. Observers A.R.H. W.B.D.

Run No	303	303a	304
Date 1918	6-11	"	"
Time	2h 44m	2:53	3:03
Humidity %	49	50	50
Barometer mm. Hg.	750	750	750
Density corr. due to excess inlet press, lbs/ft^3	+.0006	.0006	.0004
Density corr. due to humidity, "	-.0008	- 9	- 8
Density dry air "	.0703	.0702	.0705
Temp. air at entrance , C	36.2	37.1	35.7
Mean steam temp. C	100.1	100.1	99.9
Boiling temp. C	99.6	99.6	99.6
Superheat C	31.0	32.3	26.0
A H $\times 10^{-3}$	530	530	527
Water condensed, lbs.	3	3	3
Time of condensation, sec.	283	283	311
Mean steam - entrance air °C	63.9	63.0	64.2
Heat dissipated HP/ft^2/100 F	29.3	29.7	26.4
Pitot constant	3.786	3.786	3.786
Air density lbs/ft^3	.0701	.0699	.0701
Pitot reading	24.4	24.2	16.5
Air flow lbs/sec/ft^2	4.94	4.92	4.07
Press. gage constant	.393	.393	.393
Apparent press. drop lbs/ft^2	17.9	17.8	12.2
Open channel correction "	- .5	- .5	- .4
True press. drop "	17.4	17.3	11.8

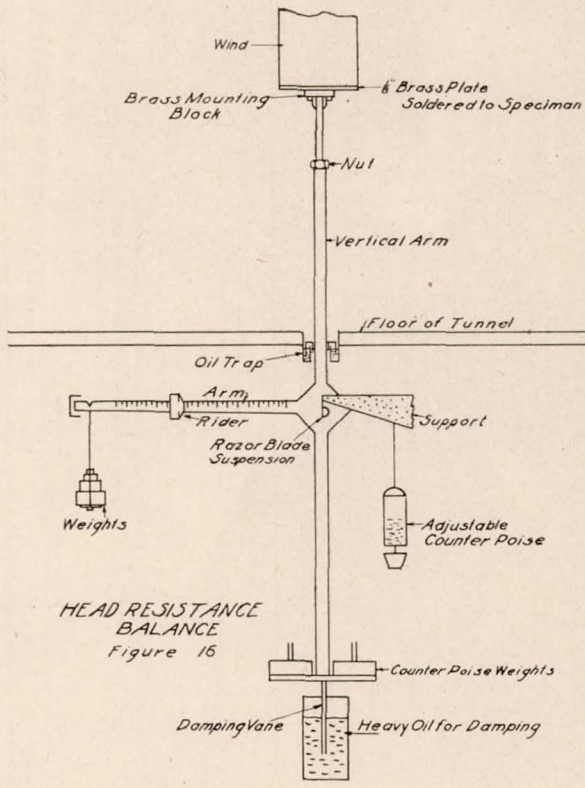
Remarks:

Figure 14

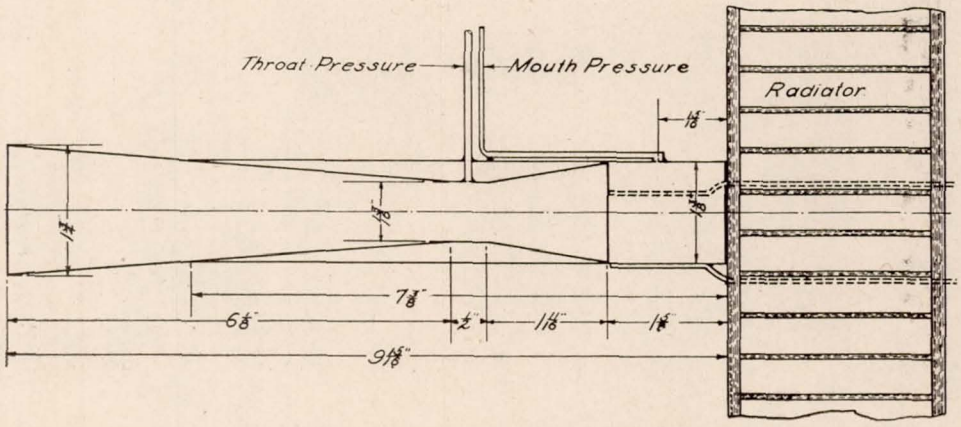


NOTE Figures show approx dimensions only

LARGE WIND TUNNEL
Figure 15



HEAD RESISTANCE BALANCE
Figure 16



SPECIAL AIR VENTURI
FOR
AIR FLOW THROUGH RADIATOR
Figure-17

Heat given up by the steam.—Let—

T_b = condensation temperature of the steam in ° C.
S = superheat in ° C.
L = latent heat in B. T. U. / pound.
C_p = specific heat of the steam.
H = heat lost by 1 pound of steam in B. T. U.
T = mean temperature of the radiator contents.

If the arithmetic mean temperature of the superheated steam and the condensation temperature are weighted according to the amount of heat lost at each temperature,

$$HT = \left(T_b + \frac{S}{2}\right) C_p S + L\, T_b \tag{17}$$

and

$$T = T_b + \left(\frac{C_p}{2H}\right) S^2 \text{ Since } H = L + C_p S \tag{18}$$

The second term of (18) is small and is a function of the superheat only (assuming C_p to be sensibly constant) so a table of values for it was prepared from steam table data.

H is likewise a function of the superheat only and was tabulated in the same way (Goodenough's Steam and Ammonia Tables 1915).

If t_s = number of seconds required to condense w pounds of steam
and Q = heat lost in H. P. / ft.²/100° F.
and $A = 176.7\ w$, 176.7 being a conversion factor, then by definition of Q

$$Q = \frac{A\,H}{t_s(T-t)} \tag{19}$$

A computation sheet, (fig. 14) is reproduced.

(3) POWER EXPENDED IN CARRYING THE RADIATOR.

The measurements needed to determine this quantity were made in a tunnel whose cross section was large compared with the dimensions of the radiator tested, in contradistinction to the heat measurements, which were all made in bulkhead tunnels. Figure 15 shows a sketch of this large tunnel.

It was of octagonal section, 54 inches in inside diameter. The entering air passed through a honeycomb of sheet metal cells, 3 inches in diameter and 12 inches deep, through a straight section of 25 feet long, and out through a conical diffuser. A four-blade propeller fan driven by a 75-horsepower direct-current motor drew air through the tunnel. A continuous speed range from 15 to 90 miles per hour could be obtained by adjustments provided by rheostats in both field and armature and two voltages, 110 and 240. A Pitot tube read on an inclined water gauge measured the air speed to 1 per cent.

The head resistance was measured directly on a balance, figure 16. This was mounted a little below the floor of the tunnel, and consisted essentially of a bell crank suspended by thin flexible steel strips, with a horizontal arm on which weights could be hung below the tunnel, and a vertical arm passing up through the tunnel floor to support the specimen. A second vertical arm extended below the fulcrum and carried counterpoises for lowering the center of gravity, and a second short horizontal arm with adjustable counterpoises provided a zero adjustment. The joint at the tunnel floor was rendered air-tight by an oil trap. The vertical arm that supported the specimen was extensible, and was fitted at the top with a detachable brass block. This was screwed to a plate $\frac{1}{8}$ inch or less in thickness, soldered to the lower side of the specimen under test.

CALIBRATION OF APPARATUS.

The tunnel cross section was explored with a movable Pitot and found to be uniform within 1 per cent at all points more than 8 inches from the wall. Silk threads strung from a fine vertical wire showed that there were considerable disturbances in the air stream in the neighborhood of the specimen, but no appreciable ones within 8 inches of the tunnel wall. This was taken to indicate that the tunnel was large enough to give free air conditions.

The balance was calibrated by applying known horizontal forces to the vertical arm and observing the balancing forces on the horizontal arm. This gave the correct factor by which to multiply the balance reading, for different lengths of the vertical arm, to obtain the true force. Ordinarily a length was chosen which made this factor unity, so that the force was read directly.

Method of observing.—The radiator specimen (without water boxes) was mounted on the vertical arm and the distance from its center to the fulcrum adjusted to the desired value. To find the position of no yaw, a specimen was set at various angles, the position of minimum head resistance assumed to represent zero yaw, and a reference point marked on the tunnel wall by sighting across the front of the radiator. The same result could be obtained by sighting through the radiator tubes at the honeycomb at the tunnel entrance. In other cases, the angle of yaw was measured roughly by sighting across the front of the section at a scale mounted on the tunnel wall. Because of fluctuations in the air speed, two observers took simultaneous readings on the balance and Pitots, since there was no sensible lag between the two instruments Nine points were usually observed.

Method of computing.—The apparent head resistance was obtained by multiplying the readings by the proper factor. By subtracting from this the force on the supporting arm (determined by a previous calibration) the force on the specimen was found. This divided by the frontal area gave the head resistance, in lb. wt. / ft.^{2}. Assuming a lift-drift ratio of 5.4. the horsepower used was,

$$\frac{1}{375}\left(R+\frac{W}{5.4}\right)V$$

Wherein

R = resistance in lb. wt./ft.^{2}.
W = core weight in lb./ft.^{2} front.
V = air speed in mis./hr.
$\frac{1}{375}$ = a conversion factor.

The speed was computed from the ordinary Pitot formula:

(20) $$V=K\sqrt{\frac{h}{d}}$$

Wherein

K = a conversion factor.
h = gauge reading.
d = air density in lb./ft.^{3}

At first the temperature, pressure, and humidity of the air were observed, and the actual air density and speed computed. The experiments, however, soon showed that the usual formula for the resistance of an airplane, i. e.,

(21) $$R=BdV^2 \ (B=\text{a constant})$$

also applied to these tests.

Accordingly a value of d in the neighborhood of the observed values was selected and used in (20) to compute V. Thus, neither the actual speed nor density were used, but such a value of V as gave, when combined with d_s (the standard density) the observed head resistance; for

Let d_a = actual density and substitute for V in (21) its value given by (20). This gives

(22) $$R = \frac{Bk^2hd_a}{d_a} = \frac{Bk^2hd_s}{d_s}$$

It is easily shown by dimensional considerations that if the exponent of the velocity is different from 2, say n, then the velocity required with d_s to give R will be

$$\left(\frac{d_s}{d_a}\right)^{\frac{2-n}{2n}} V_s \text{ instead of } V_s \left(V_s = K\sqrt{\frac{h}{d_s}}\right)$$

If, then, n were as low as 1.8 and $d_s/d_a = 1.056$ (the greatest difference from unity that occurred) this factor would be 1.003, a negligible difference from unity. d_s was taken as 0.0750 lbs./ft. corresponding to 65° F., 29.17 in Hg, 40 per cent humidity.

(4) MASS FLOW OF AIR THROUGH THE CORE.

PRELIMINARY ATTEMPTS.

Three different methods were tried for measuring the mass flow of air through the core before a satisfactory one was found.

(1) A careful and persistent attempt was made to measure the flow with a small Pitot tube behind the core, and in positions ranging from well within the cell to a few inches behind the core, but it appeared to be out of the question to use a Pitot tube in the turbulent air encountered.

(2) Threads were attached to the rear edges of the radiator to define the stream, in the hope that the air passing through the core could be followed to a position where the flow would not be too turbulent for the use of a Pitot tube, and that in such a position it would be possible to measure the velocity, and the area of cross section of the air that had passed through the core. But it was found that, even aside from the difficulty introduced by the tendency of the pull on the threads to straighten them, so that they would not truly follow the streamline, the flapping of the threads was too great, and consequently their position too indefinite to allow of measurement of the area included between them.

(3) A hot-wire anemometer was tried, and gave promise of very fair results, but before it had been thoroughly tried out, a simpler method was discovered and the use of the instrument was discontinued.

APPARATUS USED.

The method finally adopted employed a specially constructed Venturi, a longitudina section of which is shown in figure 17. The cylindrical throat and the two cones were made up from sheet copper soldered together, and the joints filed down into curves of stream-line form. A copper tube led out from a single small needle hole in the side of the throat. A piece of sheet iron bent into cylindrical form was soldered over the cones extending from 1⅝ inches before the front cone nearly to the rear end and covering the central contracted portion, which would else cause considerable resistance to the air stream. A second needle hole before the front cone was connected to a small tube which ran back along the outer surface, and turned up where it reached the tube coming from the throat. An inclined water gauge measured the pressure difference. Three wires soldered to the sides of the Venturi passed through the cells of the radiator, and were bent over in front so as to fasten the Venturi firmly in place behind the radiator.

CALIBRATION OF THE VENTURI.

Tests in the inclosed tunnel with eight different sections of widely differing types of core gave nearly the same pressure difference for same air flow through the tunnel and this was very close to that given when no radiator at all was used. For ordinary types of core this was true within about 3 per cent and with cores in which the air flow was very much obstructed within 6 per cent. No high degree of accuracy is claimed for this, but it was very convenient and sufficient for the purpose.

A calibration curve was obtained by running the Venturi in the open in the large wind tunnel against the Pitot tube of the tunnel. The square root of the Venturi pressure difference (in gms./cm^2) was plotted against the mass flow as computed from the tunnel Pitot. This is the product of the air speed in feet sec. by d_s (.0750 lb./ft.^{3}). The resulting curve was very flat, almost linear. Six calibrations at different times during a period of six months gave dentical curves.

NOTE.—This calibration was in terms of mass flow in pounds per second per square foot of Venturi mouth, and hence mass flow through radiators is per square foot frontal-core area, and not of air-tube area.

Method of observing.—The specimen under observation was mounted in the 54-inch wind tunnel in the same manner as for head resistance measurements, the Venturi was attached to the rear face, its pressure tubes connected to an inclined water gauge by means of tubes passing through a hole in the tunnel floor, and simultaneous readings taken of its pressure difference and the air speed in the tunnel. These readings were taken at from 9 to 15 different speeds for each radiator.

Method of computing.—The Venturi gauge reading was multiplied by the gauge factor to obtain grams per cm^2. The square root of this was computed and used as argument to determine the mass flow from the calibration curve. The mass flow was then plotted against V_s for each radiator.

As in the case of the head resistance, the actual air density was not needed. The reason for this is slightly different however. The Venturi really measures velocity, just as the Pitot, so that relation between its readings and those of the Pitot tubes furnish a measure of the ratio of the amount of air going through the radiator to the amount that would pass through that section if the radiator were absent. It seems permissible to assume that this ratio is independent of the air density, because the viscosity is known to be independent of the density, and its effect in this case is not large anyway.

REPORT No. 61

HEAD RESISTANCE DUE TO RADIATORS

Part I.—HEAD RESISTANCE OF RADIATOR CORES

By R. V. KLEINSCHMIDT and S. R. PARSONS.

Part II.—PRELIMINARY REPORT ON RESISTANCE DUE TO NOSE RADIATOR

By R. V. KLEINSCHMIDT.

Part III.—EFFECT OF STREAMLINE CASING FOR FREE-AIR RADIATORS

By S. R. PARSONS.

Bureau of Standards, Washington, D. C.

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REPORT No. 61.

PART I.

HEAD RESISTANCE OF RADIATOR CORES.[1]

By R. V. KLEINSCHMIDT and S. R. PARSONS.

RÉSUMÉ.

The present report deals with the head resistance of a number of common types of radiator cores at different speeds in free air, as measured in the wind tunnel at the Bureau of Standards. This work was undertaken in connection with exhaustive tests conducted at the bureau to determine the characteristics of various types of radiator cores, and in particular to develop the best type of radiator for airplanes.

Some 25 specimens of core were tested, including practically all the general types now is use, except the flat plate type, and the following is a summary of the most important results obtained:

1. The head resistance of various types of core varies greatly. The lowest is Candler ⅜-inch hexagonal tube (No. 78), 8 pounds per square foot at 90 miles per hour, while the highest is the fin and tube type (No. 92), 22 pounds per square foot at 90 miles per hour.

2. The shape and size factors are insignificant for the range covered (8 by 8 inches to 16 by 16 inches and 12 by 24 inches), there being no perceptible variation in the resistance per square foot.

3. The effect of inclining the surface of the radiator to the air stream (yawing) is, in general, to increase the resistance considerably for angles up to at least 30° to 45°. Cores of special construction vary greatly in this characteristic.

4. The horsepower absorbed by the radiator in being lifted and pushed through the air is high, being, at 100 miles per hour, roughly 5 per cent to 20 per cent or more of the total power developed by the engine. It thus appears that a small gain in radiator performance may be very appreciable at high speeds.

5. The importance of head resistance in determining the value of a radiator core depends greatly on its position in the machine.

6. The work here presented may prove of value in determining the effect of the radiator on the aerodynamical properties of the machine in which it is placed.

DESCRIPTION OF APPARATUS.

The wind tunnel in which this work was done is of octagonal section, 54 inches in inside diameter. The entering air passes through a honeycomb of sheet-metal cells of about 3 inches diameter and 1 foot depth, then through a straight section about 25 feet long, and out through a conical diffuser, at the end of which is a four-blade propeller fan driven by a 75-horsepower direct current motor, which draws air through the tunnel. The motor may be driven on either 120 or 240 volts, and further speed control is obtained by means of a field rheostat, giving ranges of air speeds from 32 to 53 miles per hour on 120 volts and from 66 to about 90 miles per hour on 240 volts. The air speed is measured by a Pitot tube, whose pressure is read on an inclined water gauge. Both the Pitot tube and the gauge have been calibrated with some care, and the measurements of air speed are good within 1 per cent.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 6.

DESCRIPTION OF THE BALANCE.

The balance on which the head resistance was obtained is designed to measure both vertical and horizontal forces, but since the present work is concerned only with the horizontal, we shall describe only the parts used, i. e., the "drift arm." The balance is mounted a little below the floor of the tunnel and consists essentially of a bell crank suspended by thin flexible steel strips, with one arm horizontal, on which weights may be hung below the tunnel, and one vertical arm passing up through the tunnel floor, supporting the specimen. A second vertical arm extends below the fulcrum, carrying counterpoises for lowering the center of gravity; a second short horizontal arm with an adjustable counterpoise provides for zero adjustment; and an oil trap makes an air-tight joint at the floor of the tunnel. The vertical arm supporting the specimen is extensible and is fitted at the top with a detachable brass block, which is screwed to a plate $\frac{1}{8}$ inch or less in thickness soldered to the lower side of the radiator section.

It will be evident that the balance measures—on the horizontal arm—the moment of the head resistance, but if the distances are known from the fulcrum to the center of pressure on the radiator, and to the point of application of the weights on the horizontal arm, the actual force is easily obtained. It is not convenient to measure these distances with accuracy, but their ratio was determined by means of a calibration of the balance. This calibration was made by applying known horizontal forces to the vertical arm and observing the balancing forces on the horizontal arm, readings being taken with the vertical arm extended to three different lengths.

PRELIMINARY INVESTIGATIONS.

A preliminary investigation, with a radiator first in one position and then inverted, showed that we may assume the center of pressure on the section to be at its geometrical center. A similar test showed the resistance of several cores to be the same whichever face was presented to the wind. An exploration of the cross section of the tunnel with a second Pitot tube showed that to within 6 or 8 inches of the wall the velocity distribution is uniform to about 1 per cent. To test whether the conditions truly represent a velocity in free air, silk threads were attached to a fine vertical wire strung about 6 inches in front of a large-sized specimen of high head resistance (Spirex, 16 by 16 inches). The threads showed a considerable curvature of the stream lines around and close to the section, but no appreciable curvature within 8 inches of the tunnel wall. This condition was taken to indicate that the effect of the radiator was confined well within the cross section of the tunnel.

METHOD OF TAKING OBSERVATIONS.

The method of taking readings is as follows: The radiator (bare core, without water boxes) is mounted on the vertical arm of the balance and the distance measured from its center to a fixed point on the arm. The distance from this point to the fulcrum was determined by the calibration mentioned above. To determine the position of no yaw, a specimen was set at various angles, the position of minimum head resistance assumed to represent zero yaw, and a reference point marked on the tunnel wall by sighting across the front of the section. It was found that the alignment could be obtained equally well by sighting through the tubes of the radiator at the honeycomb at the tunnel entrance. For yawed runs, the angle of yaw was measured roughly by sighting across the front of the section at a scale mounted on the tunnel wall. The air speed is quite sensitive to changes in voltage on the power line, and because of fluctuations it was necessary for two observers to take simultaneous readings on the balance and the Pitot tube gauge. There is, however, practically no lag between the two instruments, and very satisfactory readings can be obtained. In most cases observations were made at nine different speeds.

METHOD OF COMPUTATION.

The computation of results is simple. The head resistance is obtained by subtracting a correction for the supporting arm, which was determined by a "blank" run without a radiator, from the weights hung on the horizontal arm of the balance (including equivalent weight of the

rider) and multiplying by the proper factor to give the force on the vertical arm. All results are reduced to a frontal area of 1 square foot. Horsepower absorbed in sustaining the weight and pushing it through the air is given by the equation

$$H.\,P. = c\left(R + \frac{w}{5.4}\right)V \tag{1}$$

where $H.\,P.$ = horsepower absorbed per sq. ft.
R = head resistance in lb./sq. ft.;
w = weight of empty core, in lb./sq. ft.
V = free air speed, in mi./hr.
c = a constant representing conversion factor = 1/375.

For further computation, let
h = reading of Pitot tube gauge.
r = air density, in lb./cu. ft.
subscripts "a" and "s" denote actual and "standard" or reduced values, respectively, and
k, K = constants.

The air speed is given by the equation

$$V = k\sqrt{h/r}. \tag{2}$$

In accordance with aerodynamic practice, and with the results of observations on pressure drop through radiator sections in a closed tunnel, head resistance has been assumed to be proportional to air density, and all results have been reduced to an assumed density of 0.0750 pounds per cubic foot (corresponding to a temperature of 65° F., pressure of 29.7 in. mercury, and humidity of 40 per cent).

The correction for density may be made by the equation

$$R_s = R_a\left(\frac{r_s}{r_a}\right). \tag{3}$$

It is less laborious, however, to apply the correction for density in the computation of air speed in the following manner. Head resistance has been shown to be very nearly proportional to the square of the air speed, as well as to the first power of the density, and may be expressed by the equation

$$R = KrV^2. \tag{4}$$

Resistance at "standard" air density will be

$$R_s = Kr_sV^2, \tag{5}$$

which is the relation shown in the curves. The product (Kr_s) may be regarded as a single proportionality factor, and the same value of this factor would be obtained (and the same curve plotted), if instead of multiplying R_a by $\frac{r_s}{r_a}$ to obtain R_s, the value R_a should be substituted for R_s in equation (5), and V^2 should be divided by $\frac{r_s}{r_a}$. In other words, by substitution from equation (3), equation (5) may be written

$$R_a\left(\frac{r_s}{r_a}\right) = Kr_sV^2, \tag{6}$$

which is identical with the equation

$$R_a = Kr_sV^2\left(\frac{r_a}{r_s}\right). \tag{7}$$

From equation (2),

$$V^2 = k^2\left(\frac{h}{r_a}\right) \tag{8}$$

and

$$V^2\left(\frac{r_a}{r_s}\right) = k^2\left(\frac{h}{r_a}\right)\left(\frac{r_a}{r_s}\right) = k^2\left(\frac{h}{r_s}\right), \tag{9}$$

which is the square of the speed as it would have been computed if "standard" density had been used. Equation (9) shows that if the correction for density is to be made by dividing V^2 by $\frac{r_s}{r_a}$—or multiplying by $\frac{r_a}{r_s}$—the desired result may be obtained by the mere substitution of the "standard" density for the actual value in equation (2), when computing the air speed.

DESCRIPTION OF THE TABLES AND CURVES.

The sections tested comprise a number of different types, whose characteristics are given in Table 1. Two curves are included for each type of core, showing respectively the head resistance in pounds per square foot frontal area, and the horsepower absorbed. The latter includes, as indicated above, both that used in pushing the radiator through the air, and that required with a lift-drift ratio of 5.4 to sustain the weight of the empty core, i. e., not including the weight of water contained in the core. Extrapolations were made by means of logarithmic plots, and the extrapolated parts of the curves are indicated by dotted lines.

In order to facilitate comparison between the types, Table 2 is given, showing head resistance and horsepower at speeds of 30, 60, 90, and 120 miles per hour. It should be noted, however, that all values at 120 miles per hour and some at 90 miles per hour are given by extrapolation, and that the values of "k" are only roughly approximate. The real results are shown by the curves. To determine "k," for the equation $R=kV^2$, the head resistance curve was plotted logarithmically, and the best line with slope 2 drawn through the points. "k" was then determined from the Y intercept of this line. The line that would best fit the points had a slope somewhat less than 2, and the line drawn with the slope 2 represents an average position, in most cases intersecting the correct line at about 70 miles per hour. All extrapolations were made from the actual line, not with slope 2, and using a corresponding value of "k," not that shown in the table.

A few sections merit special comment. The curves of the Rome-Turney ¼-inch square cell (No. 81) are made up of three curves from three sizes of the section cut down twice, and the Spirex (No. 80, 82) curves are made up from two different specimens, one 12 by 24 inches and the other 16 by 16 inches; but in each case the discrepancies between the different curves were within the limit of observational error. Two sections of the "Staggard" core, one 6 by 6 inches, and one 12 by 12 inches, showed a marked difference, but it appeared that the 6-inch section was too small, and the correction for the supporting arm too large, to make its readings reliable. It is accordingly omitted from this report. On sections 8 by 8 inches up to 16 by 16 inches or larger, no results have been obtained that seem to conflict with the assumption that, within the range of sizes used, the head resistance is strictly proportional to the area, and this assumption has been used for all of these sections.

In the Livingston "electrolytic" section, the water tubes are hollow flat plates with perforations, and the perforations have the effect of whistles. The core begins to whistle at a speed of about 35 miles per hour, and five different tones were noted, which merge at 80 miles per hour into an ear-splitting shriek. As might be expected, the head resistance curve is not of the form $R=kV^n$, and the value of "k" given in Table 2 represents the curve only very roughly.

EFFECT OF YAWING.

A considerable number of the specimens were tested when turned at several angles to the air stream. The results obtained on four specimens have been plotted against the angle of the yaw (i. e., angle between the perpendicular to the face of the radiator and the direction of the wind stream), for various air speeds. The curves for Rome-Turney (No. 81) and Sparks Withington ⅜-inch elliptical cell (No. 73) are given as indicating the normal behavior of a plain cellular radiator. The head resistance increases rapidly with the angle up to at least 30°. The other plots are for special types which show the variations in the form of the curves. The Spirex is of special interest in that it shows almost no change in head resistance (per square foot frontal area of core) with changing angles up to nearly 30°. These curves are of interest in connection with the possibility of controlling the amount of cooling by yawing the radiator.

APPLICATION OF THE RESULTS.

A high head resistance is not in itself a detriment to a radiator if properly placed in the airplane. The effect of head resistance on the efficiency of a radiator in various positions is somewhat as follows:

1. A radiator placed in the open air, as between the planes or beside the fusilage, must be of low head resistance. The accompanying horsepower curves indicate the enormous consumption of power by even the best of the radiators tested, at high air speeds. It can safely be said that none of the radiators tested seem well suited for these locations if the airplane is to make the speeds required at the present time. Another consideration is the probably large volume.

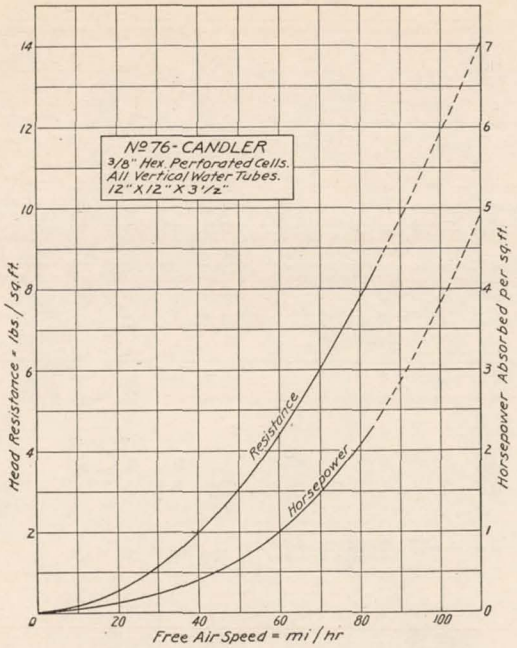
2. A radiator placed in the nose of the machine is subject to very different limitations. In this case the air has a relatively devious path to follow after passing through the core, and a high head resistance in the radiator, if accompanied by a high rate of heat transfer for a small flow of air, may not be a disadvantage. The real limit to this type of radiator is the frontal area which may be occupied. As this is usually small, a compact type of core is of advantage.

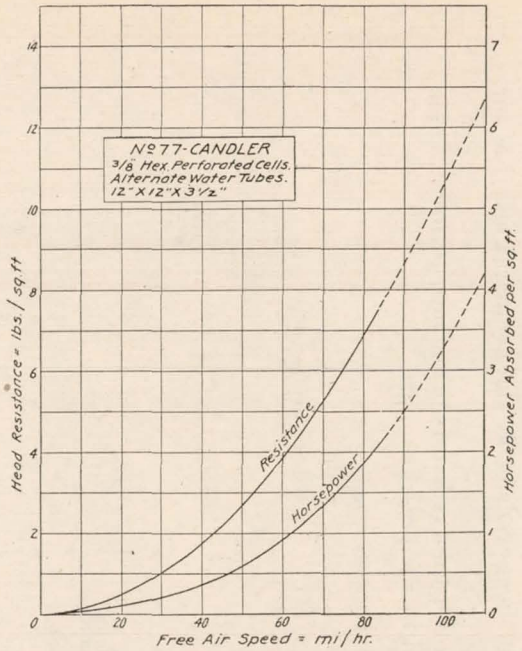
3. In the case of a radiator placed in the wing it is even more true that head resistance is of little detriment. With the small flow of air possible with a wing radiator, a high head resistance may simply increase the lift somewhat, and if it is brought about by using small air cells and turbulence vanes, it will mean a high rate of heat transfer at the comparatively low air speeds available.

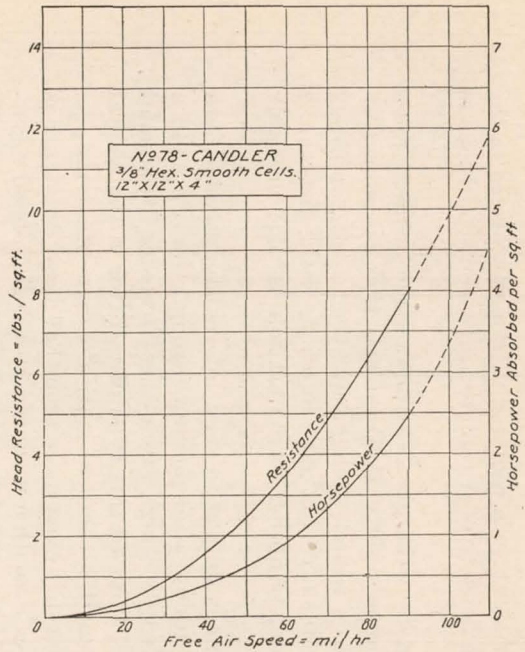
It is hoped to make tests on some flat plate water tube radiators in the near future. These are practically the only type not well represented in the present report.

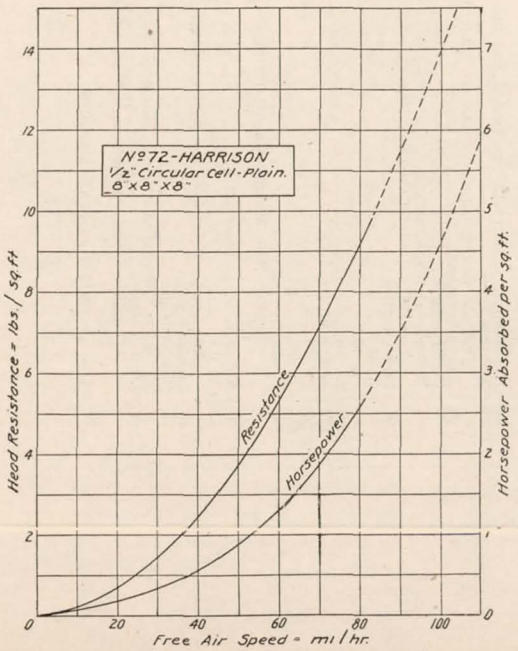
TABLE I.—*Characteristics of radiator cores.*

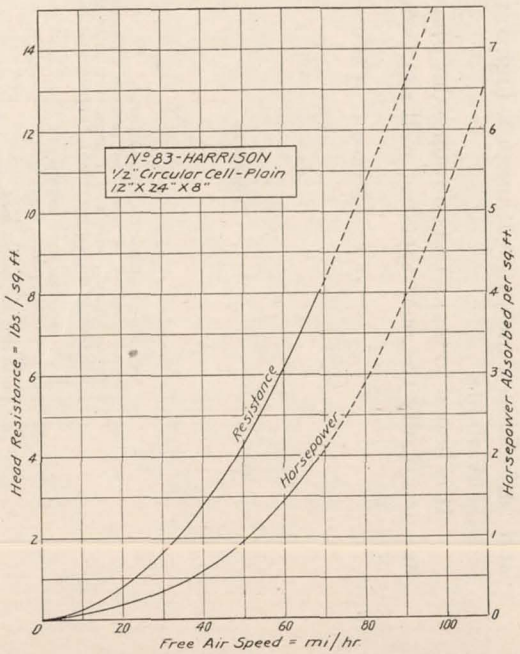
No.	Type of cell.	Depth (parallel to flow of air), inches.	Weight of core, pounds per square foot of frontal area.			Cooling surface, square feet per square foot of frontal area.
			Empty.	Water content.	Filled.	
	Candler Radiator Co., Detroit, Mich.:					
76	⅜-inch hexagonal, perforated, all verticals water tubes	3½	10.81	.....	.....	.....
77	⅜-inch hexagonal, perforated, alternate verticals water tubes	3½	9.35	.....	.....	.....
78	⅜-inch hexagonal, not perforated, alternate verticals water tubes	4	11.76	.....	.....	.....
	The Harrison Manufacturing Co. (Inc.), Lockport, N. Y.:					
72	½-inch circular, plain	8	15.68	10.70	26.38	45.7
83	.....do	8	15.31	10.70	26.01	45.7
86	½-inch circular, with vanes	8	19.2	9.9	29.1	72.0
	Livingston Radiator & Manufacturing Co., New York City:					
64	Not cellular, "electrolytic" perforated, flat tube	9½	16.34	6.39	22.73	27.8
75	5/16-inch square	5	15.55	6.17	21.72	50.1
	McCord Manufacturing Co., Detroit, Mich.:					
90	5/16-inch hexagonal	3	8.86	4.28	13.14	34.4
91	¼-inch square	3	12.55	3.03	15.58	38.2
92	Not cellular, fin and tube	3⅛	7.59	1.57	9.16	40.0
	The Mayo Radiator Co., New Haven, Conn.:					
96	¼-inch square	4 1/8	16.08	5.64	21.72	62.2
97	.....do	4 5/16	15.50	.....	.....	.....
99	.....do	3 5/16	11.87	.....	.....	.....
102	.....do	2 5/16	7.97	.....	.....	.....
100	5/16-inch square	4 1/8	13.38	.....	.....	.....
98	.....do	4 5/16	12.66	.....	.....	.....
101	.....do	3 5/16	9.43	.....	.....	.....
103	.....do	2 5/16	8.11	.....	.....	.....
	"Spirex," The Modine Manufacturing Co., Racine, Wis.:					
80	Not cellular, spiral air path	3⅜	10.98	2.64	13.62	42.8
82	.....do	3⅜	11.36	2.64	14.00	42.8
	The Sparks-Withington Co., Jackson, Mich.:					
73	⅜-inch elliptical	3½	10.53	4.35	14.88	31.9
74	¼-inch circular	3	9.95	.....	.....	.....
	Rome Turney Radiator Co., Rome, N. Y.:					
81	¼-inch square	3⅜	11.46	3.03	14.49	42.6
	"Staggard," Western Mechanical Works, Los Angeles, Cal.:					
79	5/16-inch square, crimped and staggered	4	12.96	6.76	19.72	51.6

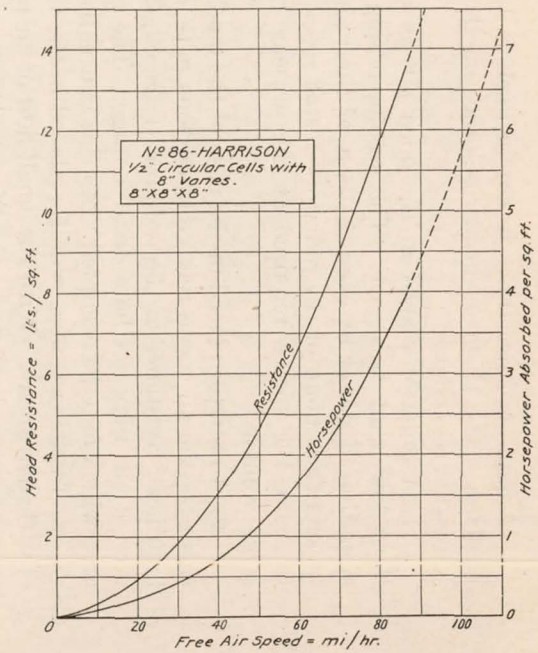

No 76 - CANDLER
3/8" Hex. Perforated Cells.
All Vertical Water Tubes.
12" X 12" X 3 1/2"
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr

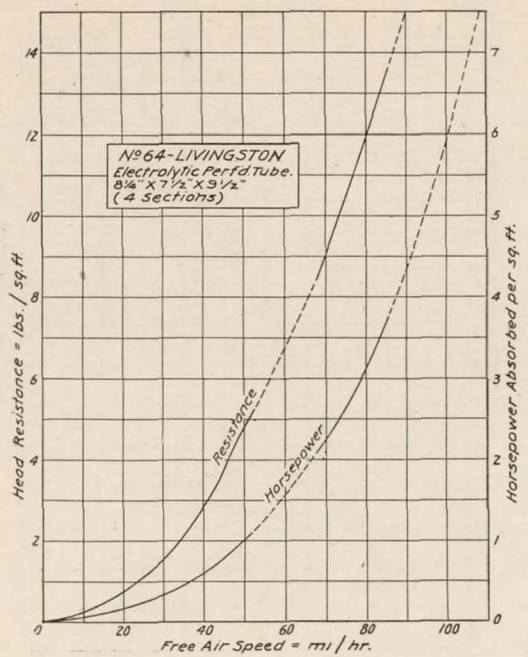

No 77 - CANDLER
3/8" Hex. Perforated Cells.
Alternate Water Tubes.
12" X 12" X 3 1/2"
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr.

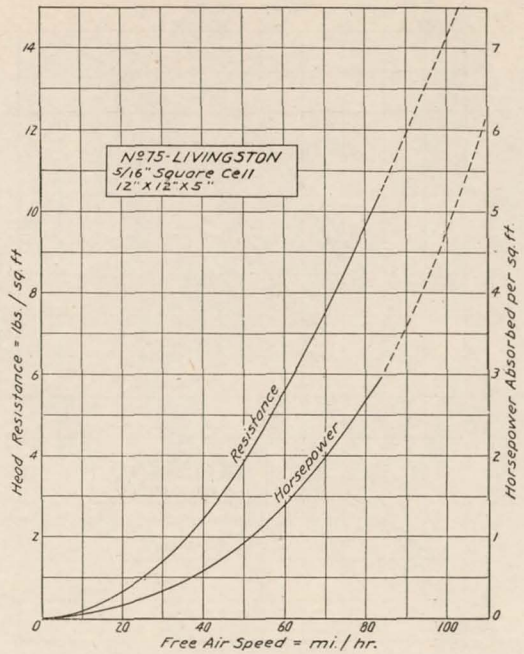

No 78 - CANDLER
3/8" Hex. Smooth Cells.
12" X 12" X 4"
Resistance
Horsepower
Head Resistance = lbs. / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr

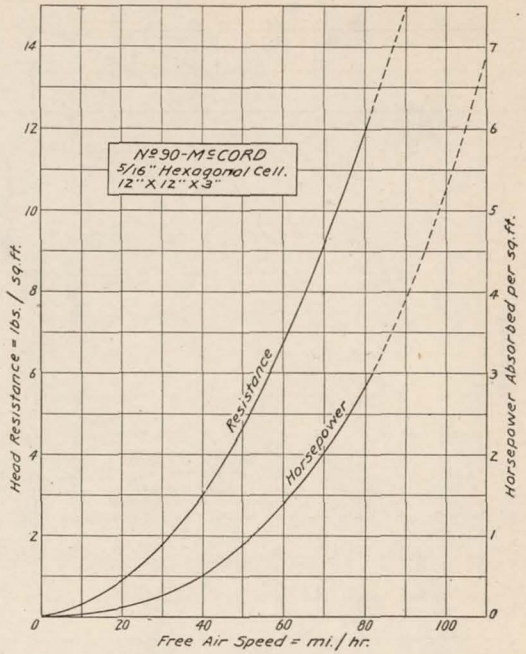

No 72 - HARRISON
1/2" Circular Cell - Plain.
8" X 8" X 8"
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr.

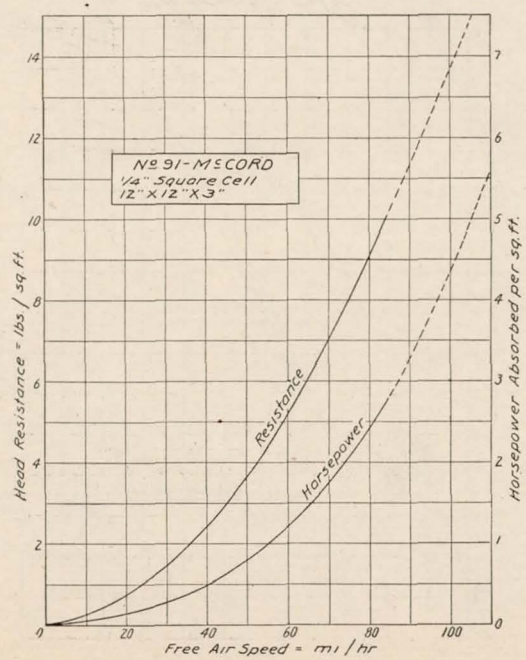

No 83 - HARRISON
1/2" Circular Cell - Plain
12" X 24" X 8"
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr.

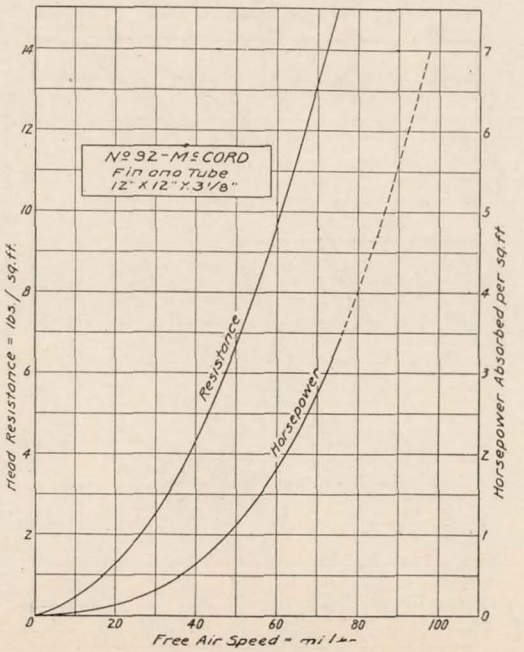

No 86 - HARRISON
1/2" Circular Cells with
8" Vanes.
8" X 8" X 8"
Resistance
Horsepower
Head Resistance = lbs. / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr.

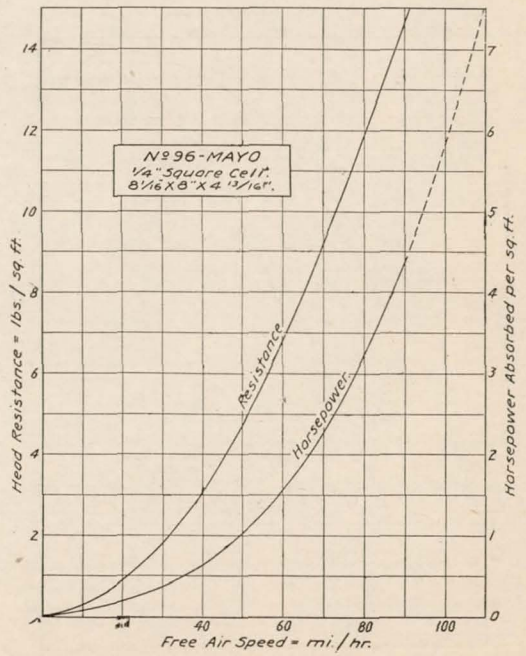

No 64-LIVINGSTON
Electrolytic Perfd Tube.
8¼" X 7½" X 3½"
(4 Sections)
Resistance
Horsepower
Head Resistance = lbs. / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr.

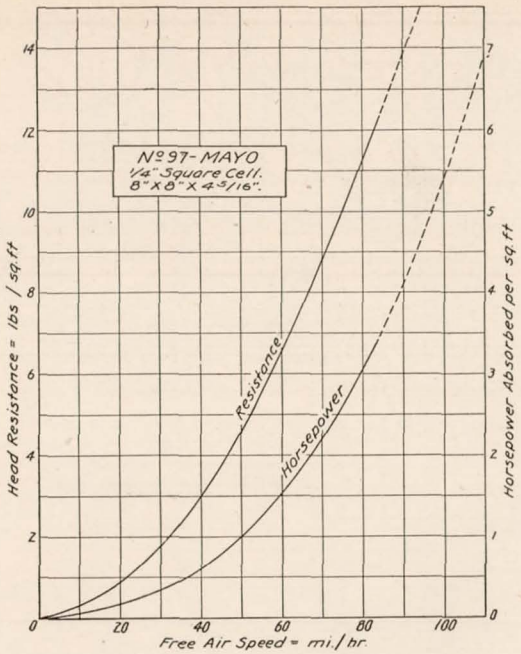

No 75-LIVINGSTON
5/16" Square Cell
12" X 12" X 5"
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq. ft.
Free Air Speed = mi. / hr.

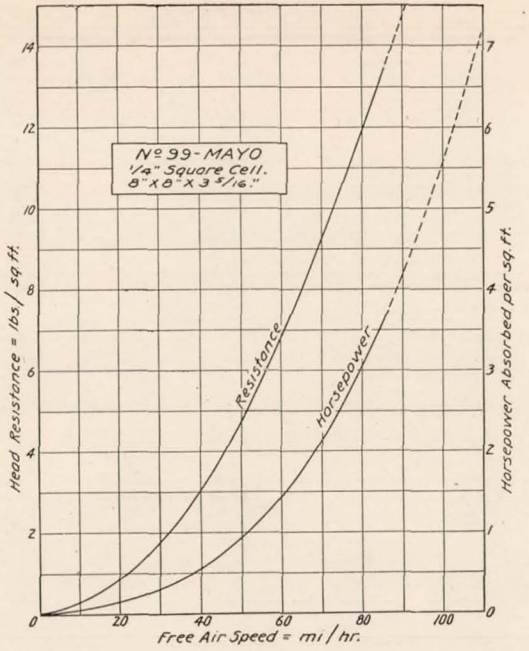

No 90-McCORD
5/16" Hexagonal Cell.
12" X 12" X 3"
Resistance
Horsepower
Head Resistance = lbs. / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi. / hr.

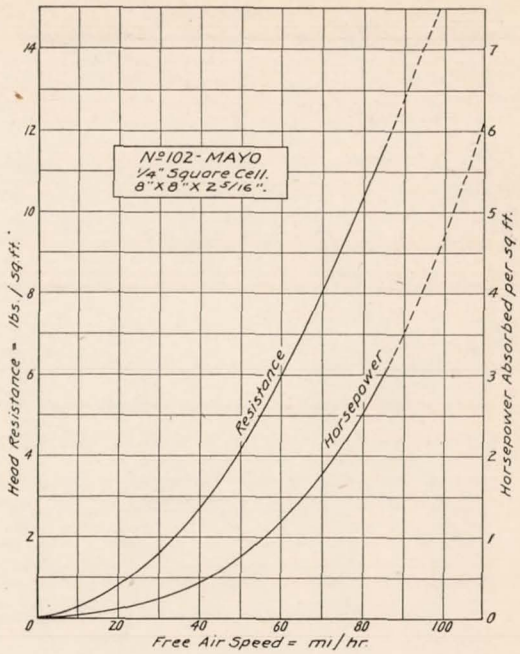

No 91-McCORD
¼" Square Cell
12" X 12" X 3"
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr

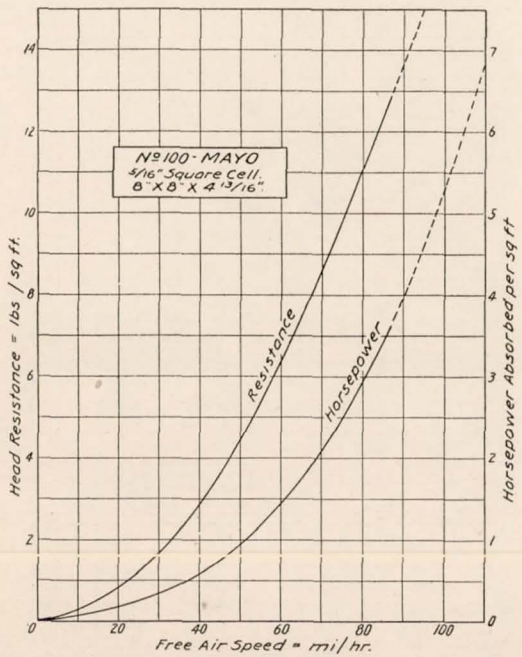

No 92-McCORD
Fin ono Tube
12" X 12" X 3 1/8"
Resistance
Horsepower
Head Resistance = lbs. / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi / hr

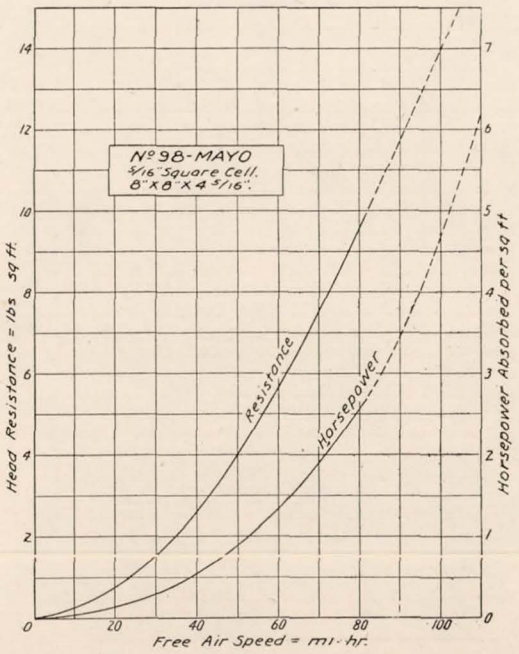

No 96-MAYO
¼" Square Cell.
8 1/16 X 8" X 4 13/16".
Resistance
Horsepower
Head Resistance = lbs / sq. ft.
Horsepower Absorbed per sq. ft.
Free Air Speed = mi. / hr.

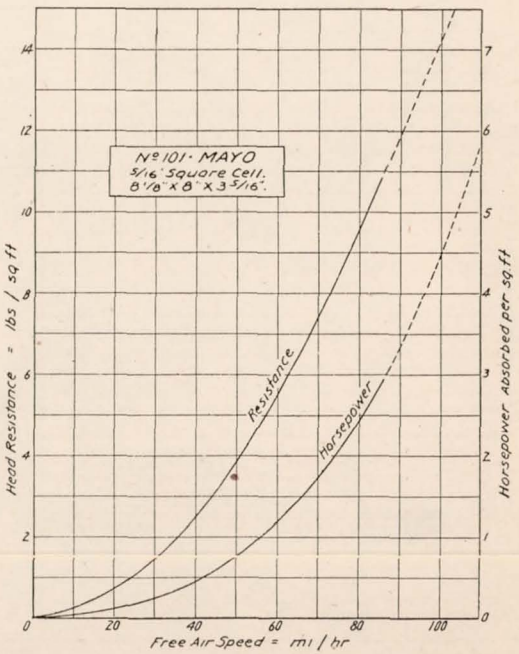

No 97 - MAYO
1/4" Square Cell.
8" X 8" X 4 5/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft.
Horsepower Absorbed per sq ft.
Free Air Speed = mi / hr.

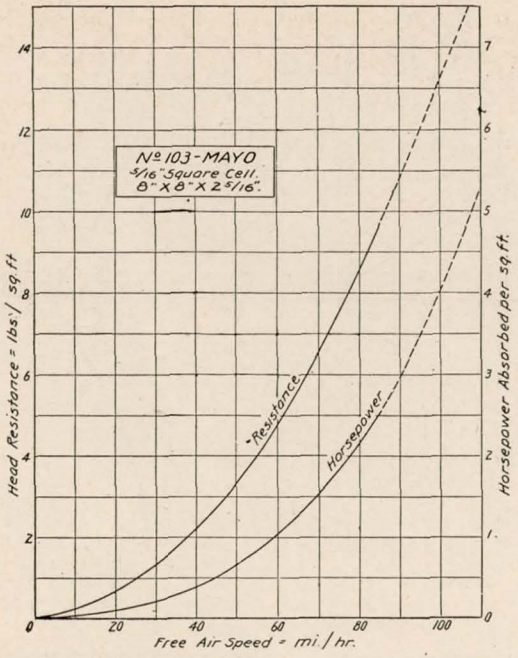

No 99 - MAYO
1/4" Square Cell.
8" X 8" X 3 5/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft.
Horsepower Absorbed per sq ft.
Free Air Speed = mi / hr.

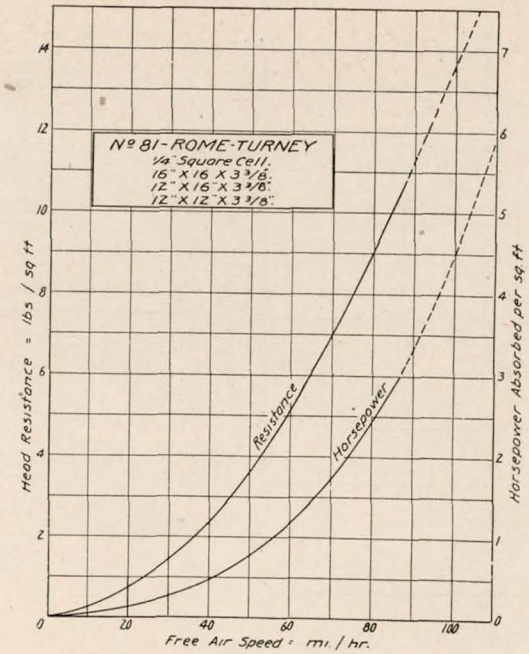

No 102 - MAYO
1/4" Square Cell.
8" X 8" X 2 5/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft.
Horsepower Absorbed per sq ft.
Free Air Speed = mi / hr.

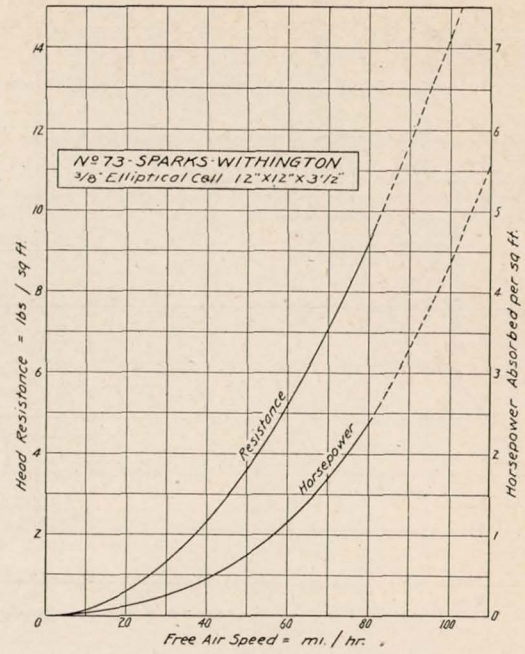

No 100 - MAYO
5/16" Square Cell.
8" X 8" X 4 13/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft.
Horsepower Absorbed per sq ft.
Free Air Speed = mi / hr.

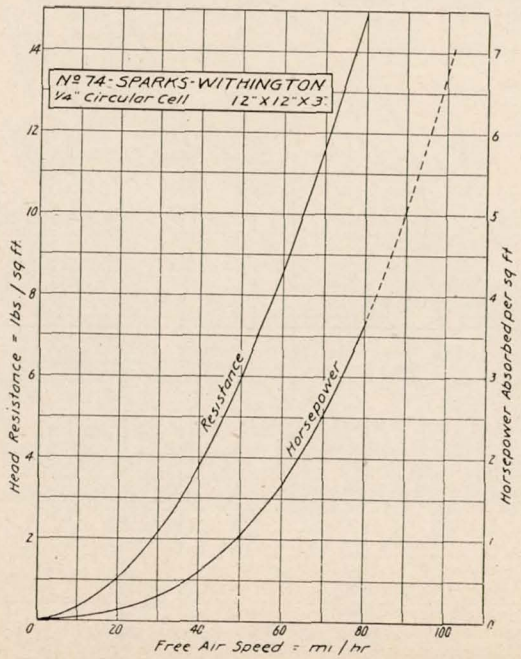

No 98 - MAYO
5/16" Square Cell.
8" X 8" X 4 5/16".
Resistance
Horsepower
Head Resistance = lbs sq ft.
Horsepower Absorbed per sq ft.
Free Air Speed = mi - hr.

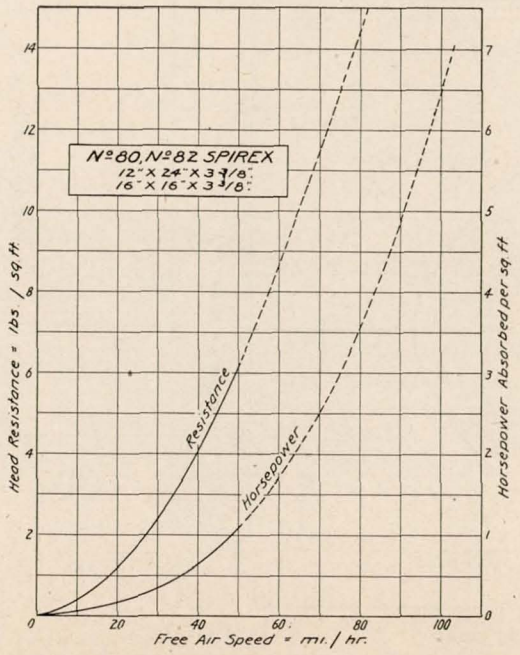

No 101 - MAYO
5/16" Square Cell.
8 1/8" X 8" X 3 5/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft
Free Air Speed = mi / hr

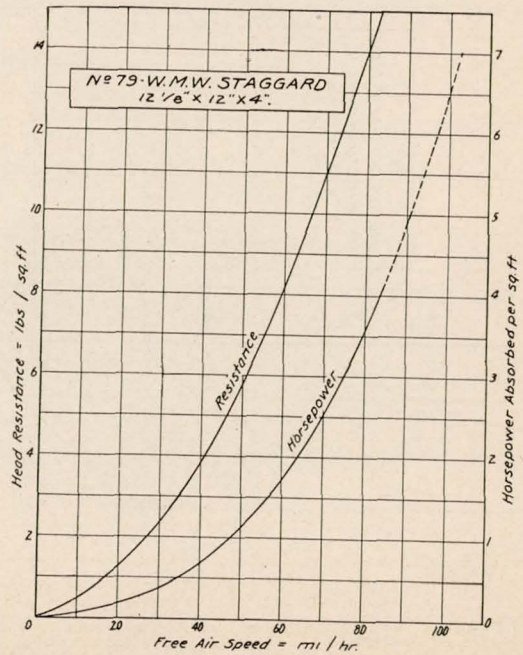

No 103 - MAYO
5/16" Square Cell.
8" X 8" X 2 5/16".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft.
Free Air Speed = mi / hr.

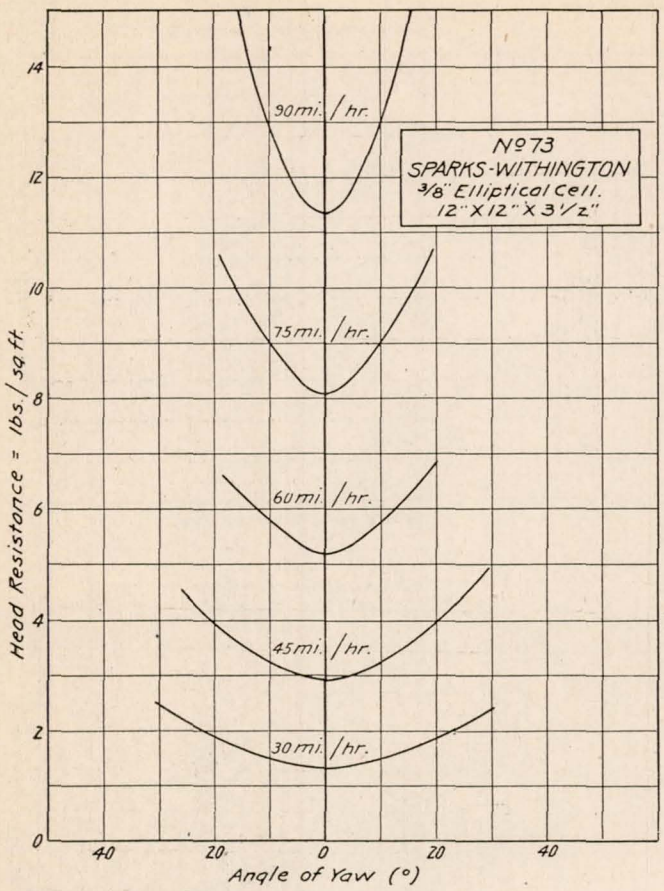

No 81 - ROME-TURNEY
1/4" Square Cell.
16" X 16 X 3 3/8".
12" X 16" X 3 3/8".
12" X 12" X 3 3/8".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft.
Free Air Speed = mi. / hr.

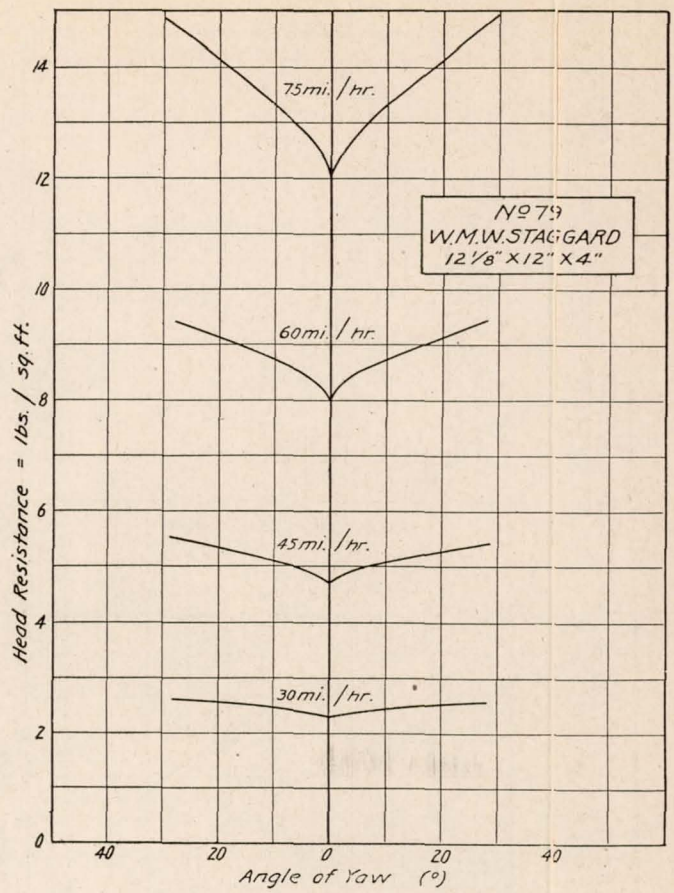

No 73 - SPARKS-WITHINGTON
3/8" Elliptical Cell 12" X 12" X 3 1/2"
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft.
Free Air Speed = mi. / hr.

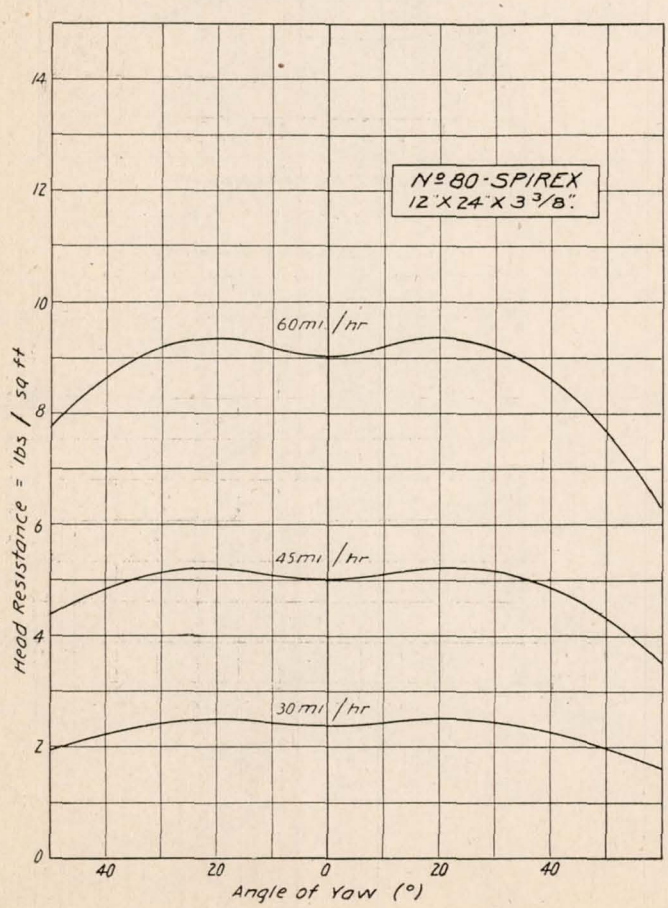

No 74 - SPARKS-WITHINGTON
1/4" Circular Cell 12" X 12" X 3".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft
Free Air Speed = mi / hr


No 80, No 82 SPIREX
12" X 24" X 3 3/8".
16" X 16" X 3 3/8".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft
Free Air Speed = mi. / hr.


No 79 - W.M.W. STAGGARD
12 1/8" X 12" X 4".
Resistance
Horsepower
Head Resistance = lbs / sq ft
Horsepower Absorbed per sq ft
Free Air Speed = mi / hr.


No 73
SPARKS-WITHINGTON
3/8" Elliptical Cell.
12" X 12" X 3 1/2"
90 mi. / hr.
75 mi. / hr.
60 mi. / hr.
45 mi. / hr.
30 mi. / hr.
Head Resistance = lbs. / sq. ft.
Angle of Yaw (°)


No 79
W.M.W. STAGGARD
12 1/8" X 12" X 4"
75 mi. / hr.
60 mi. / hr.
45 mi. / hr.
30 mi. / hr.
Head Resistance = lbs. / sq. ft.
Angle of Yaw (°)


No 80 - SPIREX
12" X 24" X 3 3/8".
60 mi / hr
45 mi / hr
30 mi / hr
Head Resistance = lbs / sq ft
Angle of Yaw (°)

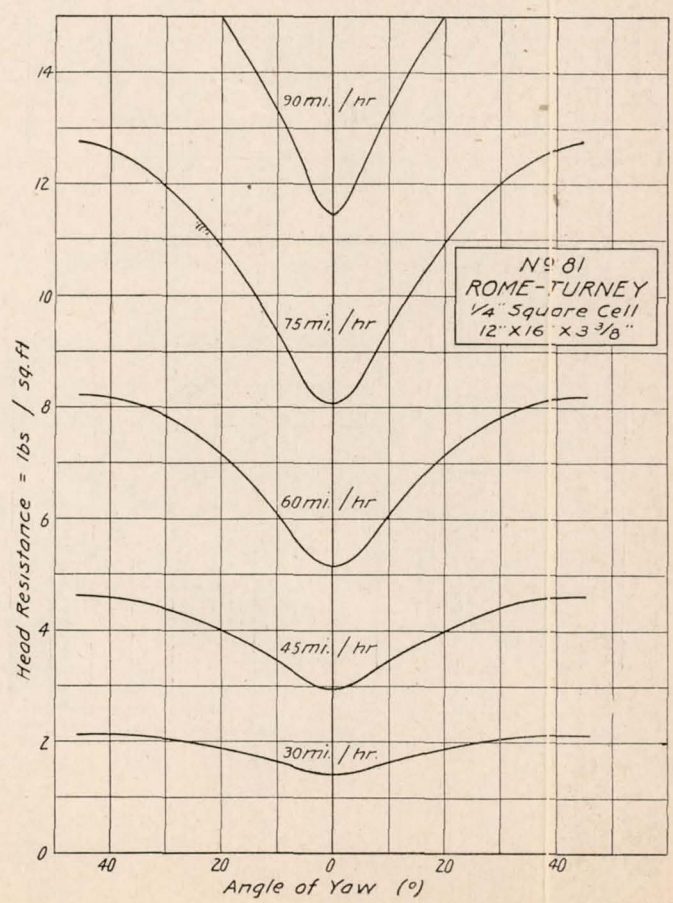

No 81
ROME-TURNEY
1/4" Square Cell
12" X 16" X 3 3/8"
90 mi. / hr
75 mi. / hr
60 mi. / hr
45 mi. / hr
30 mi. / hr.
Head Resistance = lbs / sq. ft
Angle of Yaw (°)

TABLE II.—*Comparison of head resistance of radiator cores.*

No.	Head resistance, pounds per sq. ft., at speeds in m. p. h.				Horsepower absorbed per sq. ft., at speeds in m. p. h.				$k \times 10^3$ in equation $R = k V^2$
	30	60	90	120	30	60	90	120	
76	1.14	4.40	9.80	17.3	0.25	1.01	2.83	6.18	1.24
77	1.04	3.90	8.70	14.8	.23	.92	2 48	5.29	1.13
78	.90	3.54	8.00	14.2	.23	.92	2.44	5.24	1.00
72	1.45	5.30	11.48	20.1	.34	1.30	3.44	7.36	1.46
83	1.63	6.13	13.04	22.9	.35	1.44	3.82	8.25	1.73
86	1.83	6.69	14.70	24.9	.42	1.64	4.39	9.10	1.84
64	1.60	6.80	14.96	28.1	.36	1.57	4.30	9.95	1.84
75	1.40	5.60	11.87	21.7	.35	1.37	3.52	7.87	1.54
90	1.80	6.70	14.89	25.7	.27	1.37	3.87	8.75	1.86
91	1.43	5.17	11.30	19.6	.30	1.20	3.26	7.01	1.45
92	2.55	9.61	21.5	38.1	.31	1.78	5.50	12.64	2.68
96	1.80	6.80	14.67	26.7	.39	1.55	4.35	9.50	1.88
97	1.75	6.51	13.84	24.3	.37	1.53	4.07	8.70	1.80
99	1.78	6.77	14.70	26.3	.30	1.44	4.16	9.12	1.85
102	1.61	5.96	12.77	22.6	.25	1.20	3.46	7.70	1.63
100	1.66	6.39	13.60	24.5	.33	1.42	3.95	8.63	1.74
98	1.51	5.66	11.70	21.4	.27	1.30	3.40	7.60	1.54
101	1.44	5.50	11.78	21.3	.26	1.16	3.28	7.36	1.52
103	1.34	4.73	10.73	19.2	.22	1.03	2.93	6.62	1.35
81	1.44	5.14	11.20	21.6	.27	1.17	3.27	7.59	1.46
73	1.38	5.16	11.62	20.0	.26	1.15	3.23	7.03	1.46
74	2.20	8.60	19.06	33.2	.32	1.68	5.01	11.21	2.43
80, 82	2.40	8.60	18.02	30.6	.37	1.69	4.80	10.45	2.48
79	2.35	8.17	17.70	30.3	.32	1.42	4.82	10.47	2.29

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REPORT No. 61.

PART II.

PRELIMINARY REPORT ON RESISTANCE DUE TO NOSE RADIATOR.[1]

By R. V. KLEINSCHMIDT.

RÉSUMÉ.

Wind-tunnel tests on a model fuselage show the following qualitative results:

(1) At any given plane speed the total resistance of a fuselage with a flat nose radiator is increased by increasing the air flow through the radiator either by opening exit vents for the air or by decreasing the resistance of the radiator to passage of air. This shows that a nose radiator, in contradistinction to an unobstructed radiator, should be of compact construction with high heat transfer for low air flows through the core, therefore requiring a core of high resistance.

(2) With varying plane speeds the relative efficiencies of unobstructed and nose radiators do not change.

(3) With all three widely differing types of core tried, the combined resistance of the fuselage and an unobstructed radiator of given cooling capacity was from 10 or 50 per cent less than that of the fuselage with a nose radiator of the same core construction and equivalent cooling capacity.

(4) From other experiments performed at the Bureau of Standards it is clear that there is more chance for improvement in types of core for unobstructed positions than in types of cores for the nose position.

RESISTANCE DUE TO NOSE RADIATOR.

The present report considers the effect of placing a radiator in the nose of a fuselage as compared with the effect of placing a radiator of the same core construction, having an equivalent cooling capacity, in an unobstructed position and streamlining the nose of the fuselage. The results of these tests indicate less difference than would be shown by comparing results with radiators specially selected for each of the positions in which they were placed.

The results are qualitative only, but they are so striking as to indicate that the nose of the fuselage is not a desirable location for a radiator from the point of view of head resistance.

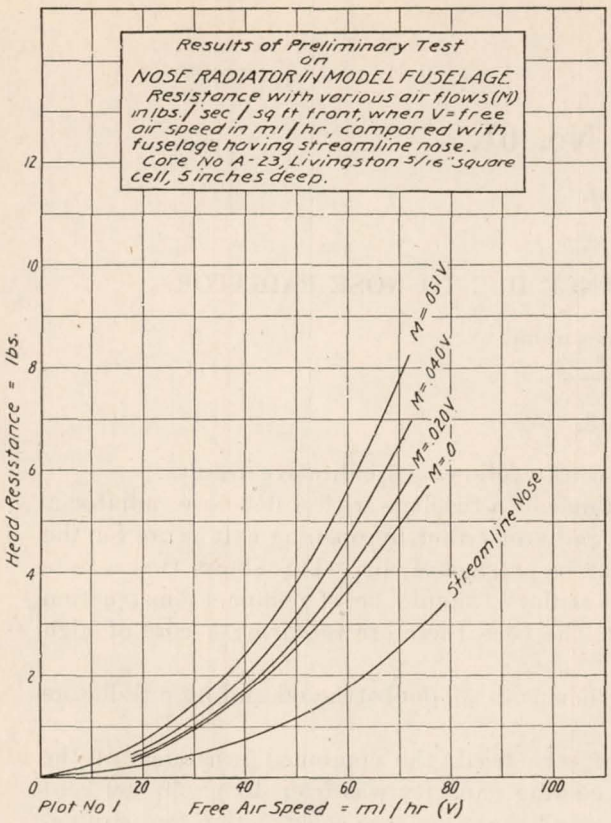
A model fuselage 60 inches long, 10 inches wide, and 13 inches high was constructed with a removable streamline nose which, when removed, allowed an 8-inch square section of radiator core to be placed in the nose. (See figures 7 and 8.) Two holes on each side of the fuselage, each about 1½ by 6½ inches, were cut about a foot back from the nose and fitted with adjustable sliding doors. By adjusting these vents the amount of air passing through the nose was varied.

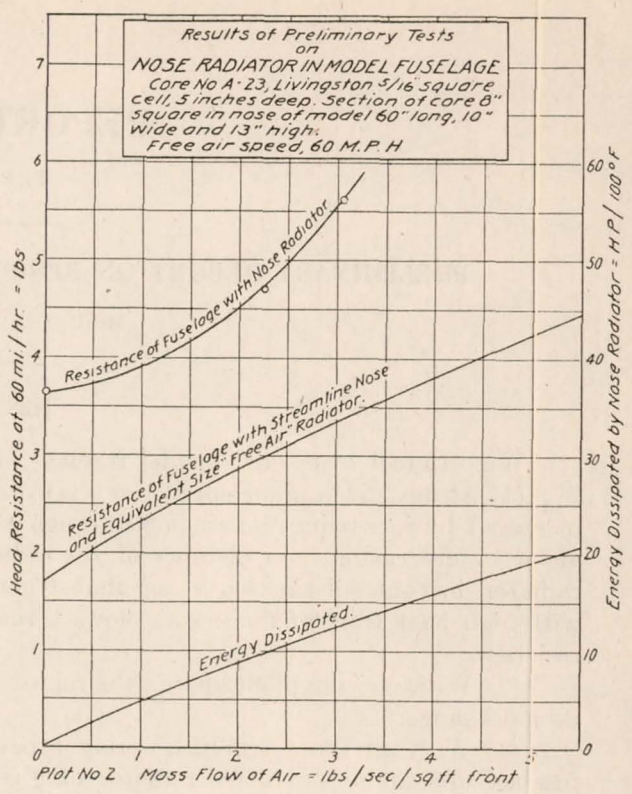
The model was mounted in a 54-inch wind tunnel and the head resistance measured under the following conditions:

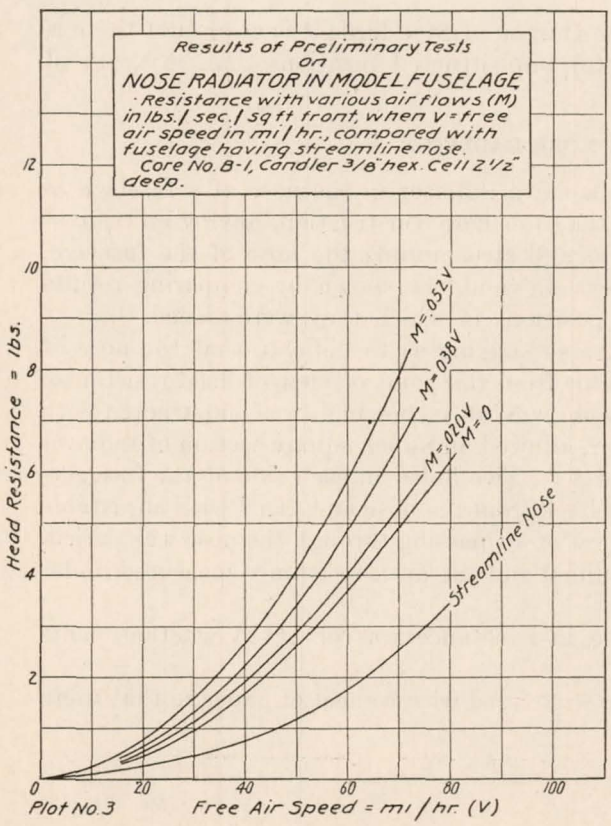
(1) Streamline nose on model. (No change in resistance was observed whether vents were open or closed.)

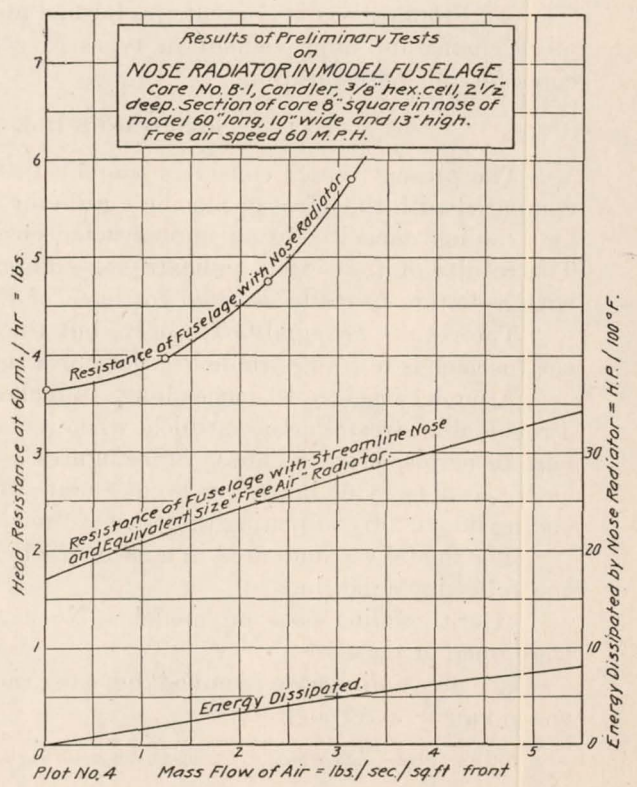
(2) Streamline nose removed, but nose radiator covered with a sheet of paper so that there was no air flow through the core.

[1] This Report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 24.


Results of Preliminary Test
on
NOSE RADIATOR IN MODEL FUSELAGE.
Resistance with various air flows (M) in lbs./sec./sq ft front, when V = free air speed in mi/hr., compared with fuselage having streamline nose.
Core No A-23, Livingston 5/16" square cell, 5 inches deep.
M = 051V
M = 040V
M = 020V
M = 0
Streamline Nose
Head Resistance = lbs.
Plot No 1
Free Air Speed = mi/hr (V)


Results of Preliminary Tests
on
NOSE RADIATOR IN MODEL FUSELAGE.
Core No A-23, Livingston 5/16 square cell, 5 inches deep. Section of core 8" square in nose of model 60" long, 10" wide and 13" high.
Free air speed, 60 M.P.H
Resistance of Fuselage with Nose Radiator
Resistance of Fuselage with Streamline Nose and Equivalent Size "Free Air" Radiator.
Energy Dissipated.
Head Resistance at 60 mi./hr. = lbs.
Energy Dissipated by Nose Radiator = H.P./100°F.
Plot No 2
Mass Flow of Air = lbs/sec/sq ft front


Results of Preliminary Tests
on
NOSE RADIATOR IN MODEL FUSELAGE.
Resistance with various air flows (M) in lbs./sec./sq ft front, when V = free air speed in mi/hr., compared with fuselage having streamline nose.
Core No. B-1, Candler 3/8" hex. Cell 2 1/2" deep.
M = 052V
M = 038V
M = 020V
M = 0
Streamline Nose
Head Resistance = lbs.
Plot No. 3
Free Air Speed = mi/hr. (V)


Results of Preliminary Tests
on
NOSE RADIATOR IN MODEL FUSELAGE.
Core No. B-1, Candler, 3/8" hex. cell, 2 1/2" deep. Section of core 8" square in nose of model 60" long, 10" wide and 13" high.
Free air speed 60 M.P.H.
Resistance of Fuselage with Nose Radiator
Resistance of Fuselage with Streamline Nose and Equivalent Size "Free Air" Radiator.
Energy Dissipated.
Head Resistance at 60 mi./hr. = lbs.
Energy Dissipated by Nose Radiator = H.P./100°F.
Plot No. 4
Mass Flow of Air = lbs/sec/sq ft front

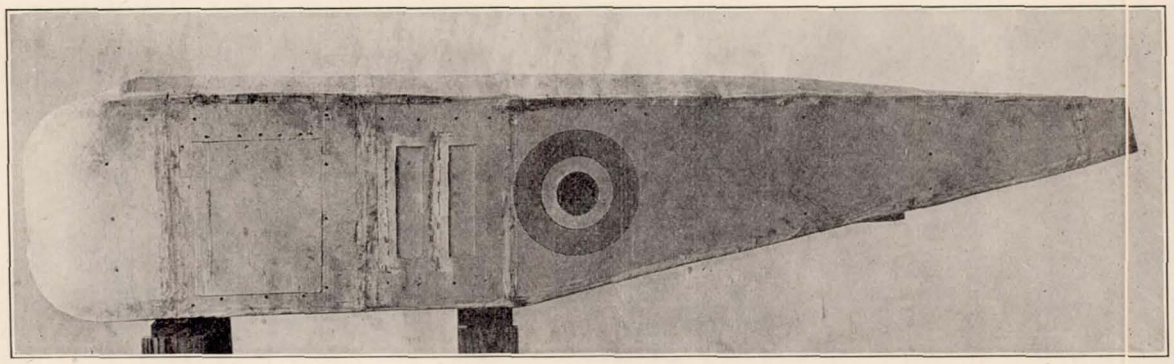


Fig. 7

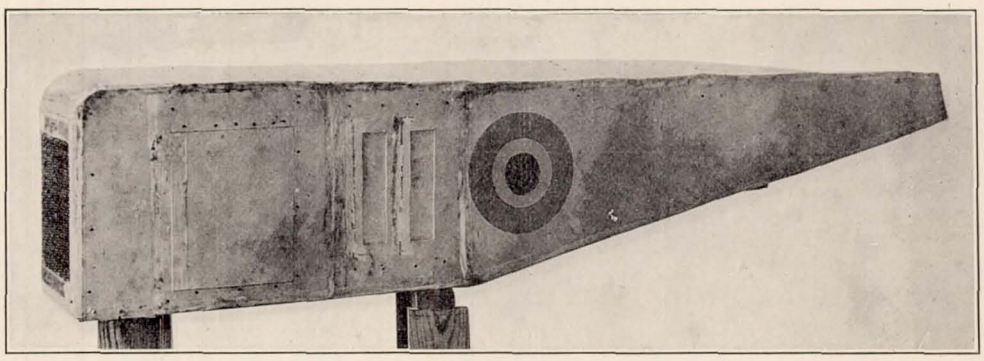
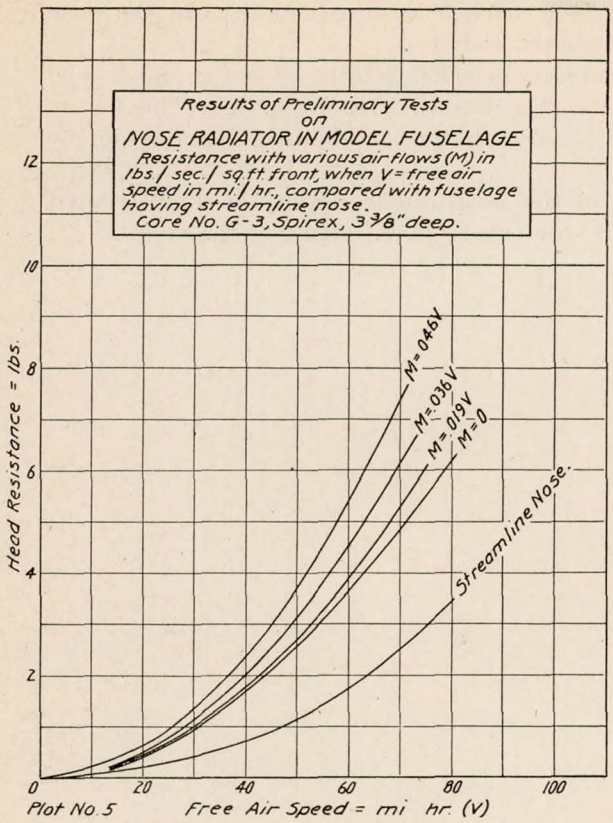
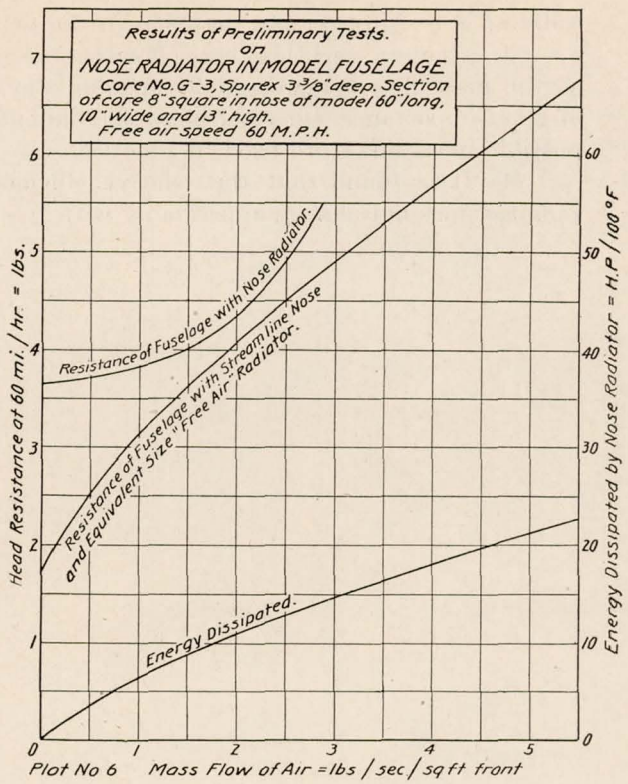


Fig. 8





(3), (4), and (5) Nose radiator in place with varying amounts of air flow controlled by opening the vents. Seven or eight different air speeds were tried in each case, the maximum being about 70 miles per hour.

The results of these runs are given in plot 1 against free-air speed. They show (1) that the streamline nose decreases the resistance of the fuselage by 50 per cent, and (2) that the total resistance of the fuselage increases rapidly when air is allowed to enter the radiator, so that a compact type of core is desirable for this position.

Plot 2 illustrates these conclusions more clearly, since there the resistance of the fuselage at 60 miles per hour free-air speed is plotted against the mass flow of air through the radiator. There is also plotted the total resistance of the fuselage with a streamline nose together with an unobstructed radiator of the same core construction and of such size as to have a cooling capacity equivalent to that of the nose radiator at any given mass flow. Plots 3, 4, 5, and 6 give the same data for two other cores, 3 and 4 being for a core of very low head resistance and 5 and 6 for a core of very high head resistance, which would be a very good type for a nose radiator and a very bad type for an unobstructed position. There are types of core considerably better for unobstructed positions than those included in this test, while the core represented in plots 5 and 6 is probably one of the best for the nose position.

CONCLUSIONS.

Based on the results of these wind-tunnel experiments on a model fuselage it is concluded that:

(1) The resistance of a fuselage with streamline nose is increased more by removing the streamline nose and substituting a radiator than it is by adding an equivalent unobstructed radiator and retaining the streamline nose.

(2) Between good radiators for each position the increase of resistance due to the nose radiator is roughly double that due to the unobstructed radiator.

(3) Above a very low mass flow the nose radiator becomes relatively worse and worse, as the mass flow is increased by opening the vents at a constant free-air speed. This fact is of great importance, since the space available for a nose radiator is so limited that the highest possible mass flows are used in practice.

(4) It is found that the relative efficiency of the nose radiator and the unobstructed radiator does not change appreciably with free-air speed for a given setting of the vents.

REPORT No. 61.

PART III.

EFFECT OF STREAMLINED CASING FOR FREE-AIR RADIATORS.

By S. R. Parsons.

RÉSUMÉ.

This report on preliminary tests of a radiator inclosed in a streamlined casing shows that head resistance can be decreased by as much as 50 per cent, but the accompanying decrease in mass flow of air, and consequently in heat transfer, nullifies the advantage gained, with a possible exception in the case of very high speeds.

DESCRIPTION OF RADIATOR AND CASING.

The radiator used was a 12-inch square section of core, composed of one-fourth inch square cells, and $3\frac{3}{8}$ inches deep. The casing, which was made of galvanized iron, is illustrated in figure 1. It is streamlined in one dimension only; the top and bottom pieces being flat rectangular sheets, and the side pieces curved. The curves used are not of the common streamline form, but are arcs of circles, because of the fact that the air flows on both sides of the sheet.

EFFECT OF CASING ON PROPERTIES OF THE RADIATOR.

The casing causes a very considerable reduction in both the head resistance and the mass flow of air through the core. As the side pieces are brought nearer together and the area of the mouth reduced, the head resistance first decreases to a minimum, and then increases. The lowest head resistance found was about 50 per cent of that of the uncased core, with a mouth area equal to one-half of the frontal area of the core. For the only section on which reliable measurements of mass flow have yet been made,

$$\frac{\text{mass flow through streamlined core}}{\text{mass flow through unstreamlined core}} = \frac{\text{area of mouth}}{\text{area of radiator face}}$$

A decrease in mass flow of air causes a decrease in heat transfer, and the advantage of the reduction in head resistance is outweighed by the disadvantages of the decrease in heat transfer and the additional weight of the casing. Plot 2 shows the figure of merit resulting from openings of the casing 9 inches, 6 inches, and 3 inches wide. To show the effect of weight, the figure of merit has been computed for a casing of galvanized iron, and also for one of aluminum. At high speeds the effect of weight is small in comparison with that of head resistance, and the curves are not far below the curve for the unstreamlined core, but they will not reach it at speeds below 100 m. p. h., and probably not at higher speeds. If there is to be any gain in figure of merit, at the lower speeds, the proportional decrease in head resistance must be decidedly greater than the proportional decrease in mass flow of air. Since, however, the decrease in heat transfer at high speeds is somewhat less for a given decrease in mass flow than at low speeds, it may be that for a speed of 150 m. p. h. there will be an advantage. The data at present available do not warrant extrapolation to such a speed.

POSSIBLE ADVANTAGE FOR MASKING.

It seems that if there is to be any considerable advantage in using the streamlined casing it will be in its adaptability for masking a part of the core. It would be a simple problem in construction to streamline the water boxes in the vertical dimension and the core in the horizontal, and to place inside of the casing for the water boxes, the mechanism for opening and closing the mouth of the casing for the core.

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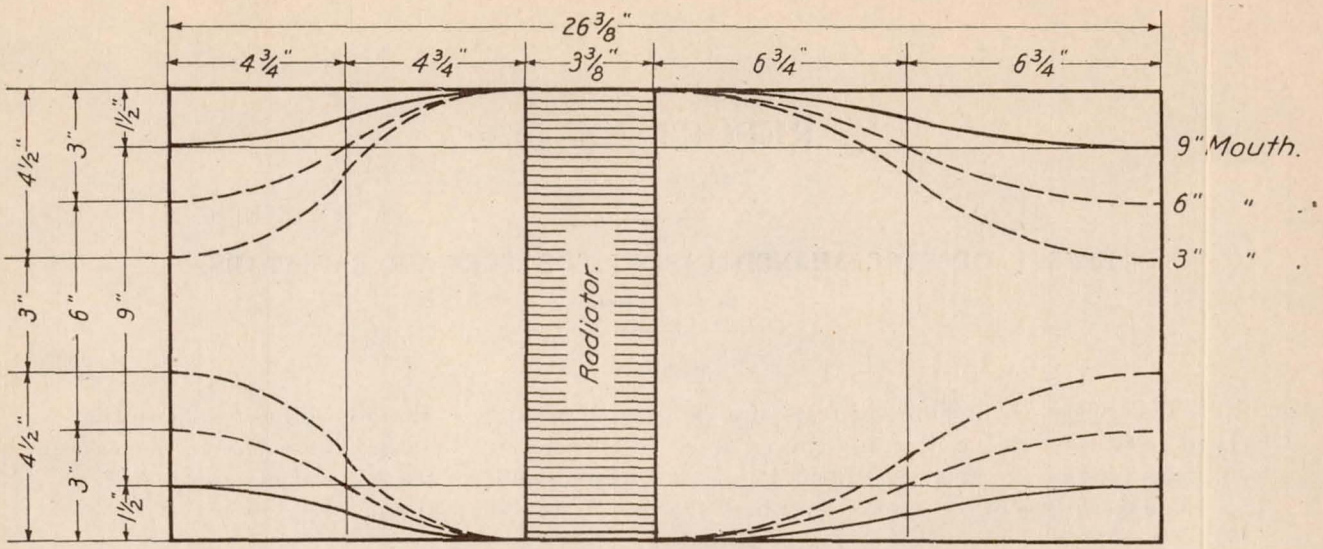
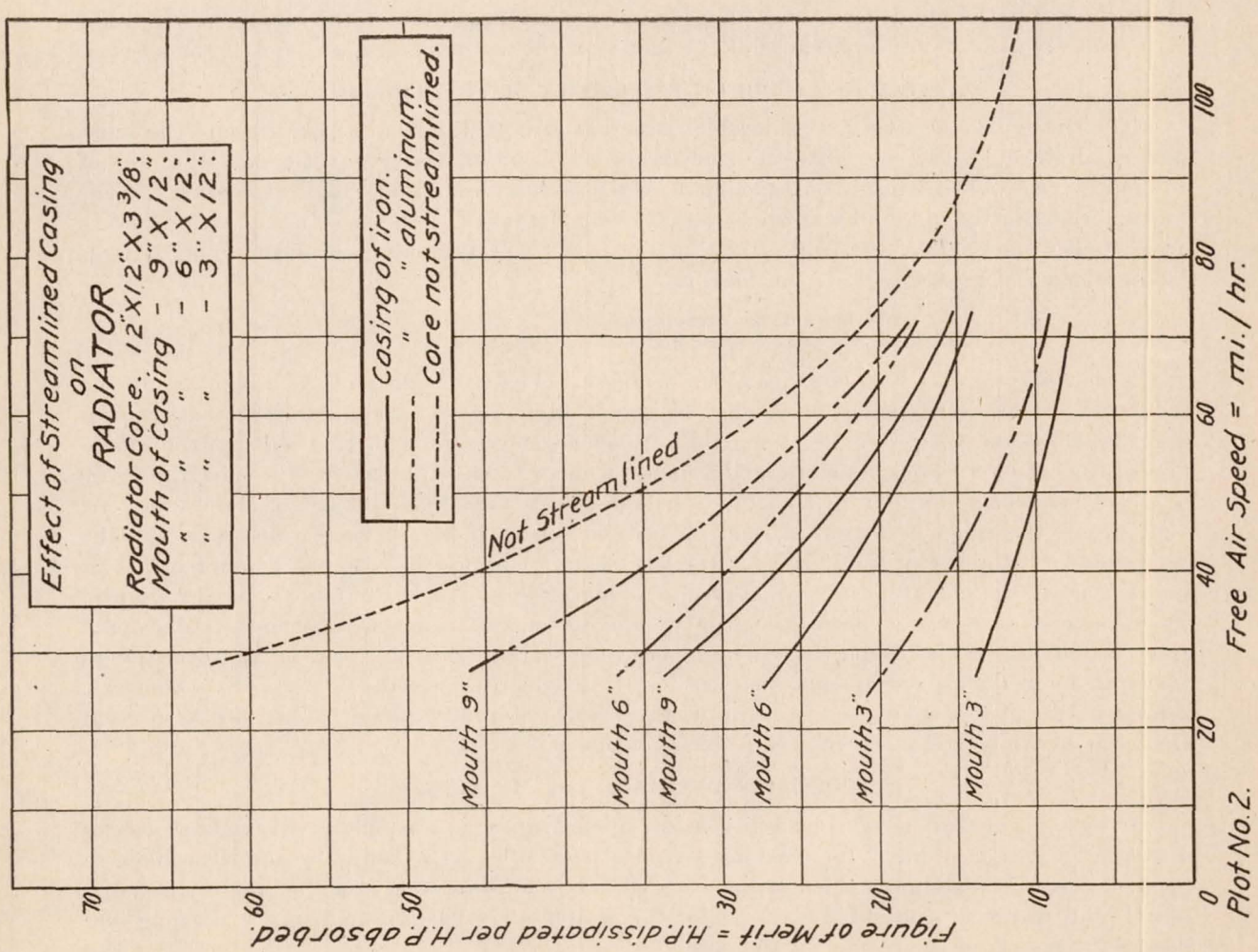


Diagram of Radiator Casing

Fig. 1.



Plot No. 2.

REPORT No. 62

EFFECT OF ALTITUDE ON RADIATOR PERFORMANCE

By W. S. JAMES AND S. R. PARSONS

Bureau of Standards, Washington, D. C.

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REPORT No. 62.

EFFECT OF ALTITUDE ON RADIATOR PERFORMANCE.[1]

By W. S. James and S. R. Parsons.

RÉSUMÉ

As an airplane rises to high altitudes the decrease in the density and the temperature of the air have important effects on the performance of the radiator.

The effect of the lower temperature tends to increase the heat transfer in proportion to the increase of the mean temperature difference between the water in the radiator and the air through which the radiator passes.

The decrease in density of the air reduces the mass of air passing through the radiator for a given plane speed, and thus tends to decrease the heat transfer by an amount corresponding (but not proportional) to the decrease in density.

Since head resistance is proportional to density of the air, the effect of decrease in density is to reduce the head resistance by an amount proportional to the decrease of density.

The combined effect of density and temperature changes is to decrease the heat transfer, but head resistance is decreased more rapidly, and for the higher plane speeds the figure of merit is, in general, increased. On the other hand, at the higher altitudes only half (or even less) of the cooling capacity may be required.

If the performance of the radiator at the ground is known (from laboratory tests or otherwise), the density of the air and the temperature difference between air and water at an altitude may be estimated from data contained in the curves of plots 1, 2, and 3 and from the conditions under which the airplane is to be used; and with this information at hand the performance of a radiator at an altitude may be estimated for a particular speed of the airplane at a particular altitude, as follows:

1. To obtain the energy dissipated, first find the mass flow of air through the radiator at the ground and at the desired speed and multiply this value by the ratio of the air density at the altitude to the density at the ground to obtain the mass flow of air at the altitude.

2. Now, from the results of tests at the ground obtain the energy dissipated per 100° F. temperature difference between air and water for the mass flow computed for the altitude, and multiply this value by the estimated temperature difference at the altitude divided by 100 to obtain the energy actually dissipated at the altitude.

3. For head resistance multiply the value at the ground and at the desired speed by the ratio of the density at the altitude to the density at the ground.

4. Horsepower absorbed is computed as at the ground by adding to the head resistance the quotient obtained by dividing the weight per square foot of the radiator filled with water by the lift-drift ratio of the plane and multiplying this sum by the plane speed and the proper conversion factor.

5. Figure of merit, as at the ground, is the ratio of the energy dissipated to the horsepower absorbed.

Plots Nos. 4 to 7 show the effect of altitude on energy dissipated and figure of merit for two typical radiators, and plot No. 8, which shows the ratio of air density at an altitude to density at the ground, indicates the proportional decrease of head resistance with increase of altitude for any type of radiator.

[1] This report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 29.

INTRODUCTION.

The efficiency of a radiator for airplane engines depends primarily upon two factors: (1) Its capacity for dissipating heat and (2) its absorption of engine power because of the necessity of pushing it through the air (overcoming its head resistance) and of lifting and sustaining its weight.

At high altitudes both the density and the temperature of the air are less than at the ground, and the change in these conditions has an important effect upon the performance of the radiator. The decrease in air temperature tends to increase the cooling capacity, while the decrease in density of the air tends to decrease both the cooling capacity and the absorption of power for any given speed of the airplane. On the other hand, the power of the engine, and consequently the heat to be dissipated, falls off with altitude, so that at high altitudes a given engine may be kept cool by a smaller radiator than that required for the same conditions of speed and climb near the ground.

PURPOSE.

The purpose of this report is, by showing the effect of temperature and density of the air on dissipation of heat and absorption of power, and with the use of available data on atmospheric conditions at altitudes, to present a method for estimating the performance of a radiator under altitude conditions in terms of its performance at the ground. A brief discussion will also be given of the relative cooling capacity required at altitudes and at the ground.

Since atmospheric conditions are continually changing, it will be evident that any estimate of performance at an altitude must be based upon assumed *conditions*, such, for example, as mean summer density and temperature of air, in addition to assumed *requirements* of operation, such as the maximum allowable water temperature. Certain meteorological data have accordingly been included, in order to give such basis as is available for the assumptions that must be made.

DEFINITIONS OF UNITS.

The results of tests at the ground are expressed as follows:

Free air speed (the speed of the airplane), in miles per hour.

Mass flow of air through the radiator, in pounds per second per square foot frontal area.

Energy dissipated (heat transfer), in horsepower per square foot of frontal area per 100° F. difference between the temperature of the entering air and the average of the temperatures of the entering and leaving water, at ground. (At an altitude this temperature difference may be modified.)

Head resistance, in pounds per square foot frontal area.

Horsepower absorbed, in horsepower per square foot frontal area, including both that used in overcoming head resistance and that used in sustaining and lifting the weight of the radiator and contained water, assuming for the airplane a lift-drift ratio of 5.4.

Figure of merit is defined as the ratio of the energy dissipated to the horsepower absorbed.

BASIS OF THE METHOD.

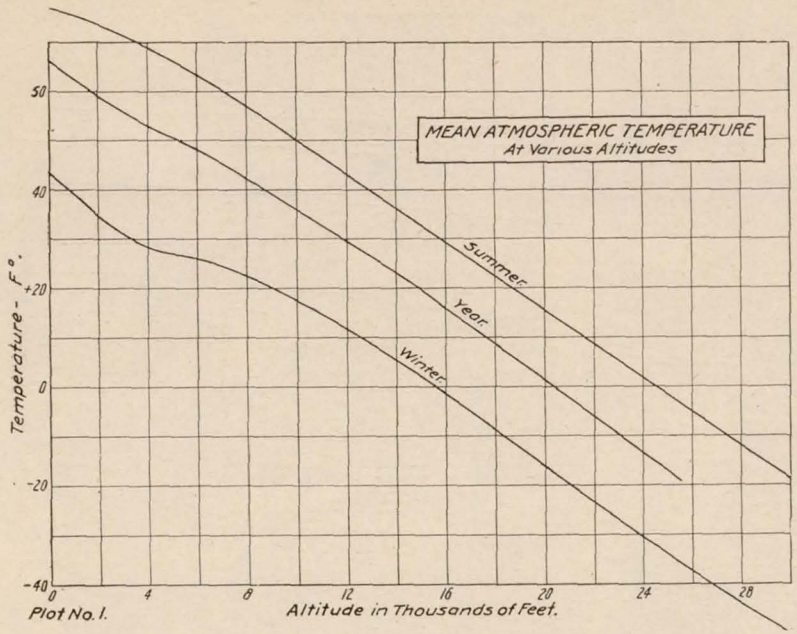
The method of estimating radiator performance under altitude conditions is based upon the following laws:

1. Mass flow of air, for a given speed of the airplane, is proportional to the air density.

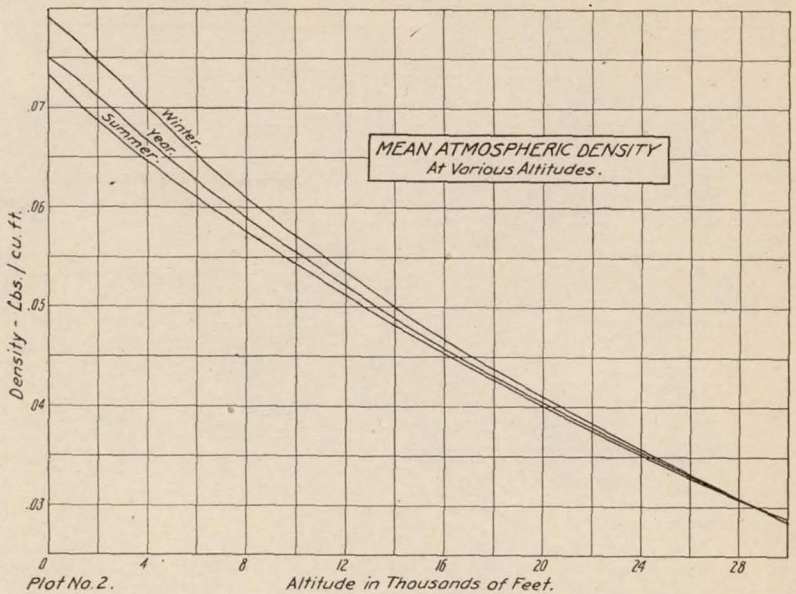
2. Energy dissipated (rate of heat transfer), for a given mass flow of air, is independent of air density. This fact is shown by a series of tests conducted on a number of specimens in a wind tunnel which was entirely inclosed in a steel tank so that the air could be partially exhausted. The range of air densities used corresponds to altitudes up to about 25,000 feet. Plot No. 10 shows the results of these tests.[1]

3. Energy dissipated for a given mass flow of air may be regarded as proportional to the temperature difference indicated under "Definitions of terms." Several investigators have

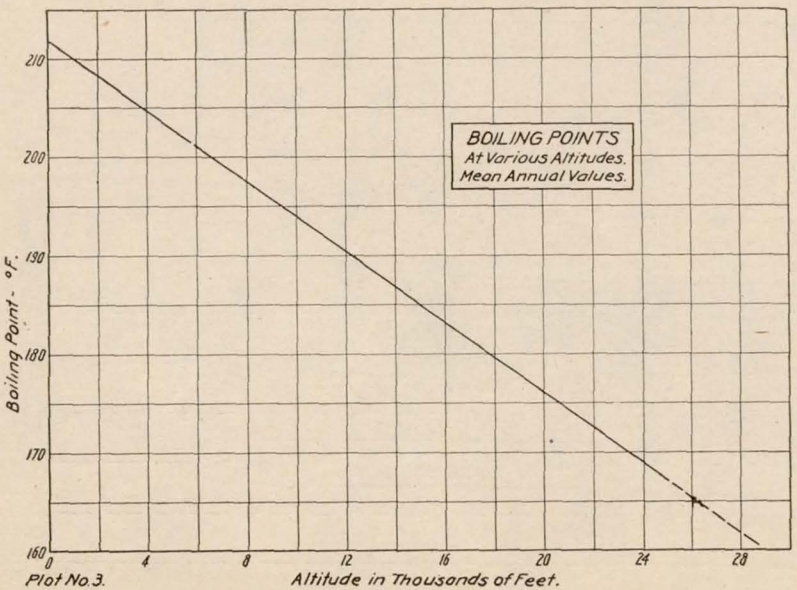
[1] The same result has previously been observed for a single copper tube with air densities equal to and greater than atmospheric. See Zeit. des Ver. deutscher Ing. 53; 43; p. 1750, Oct. 23, 1909.



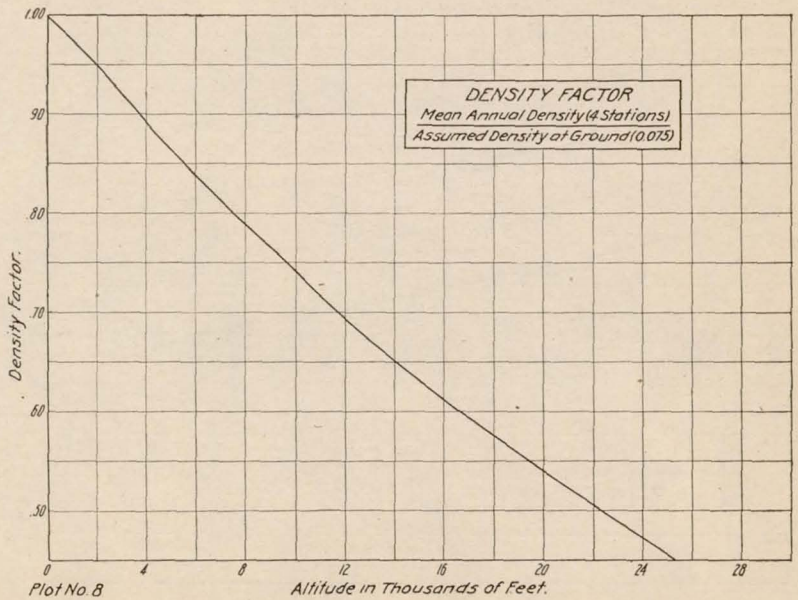
Plot No. 1.



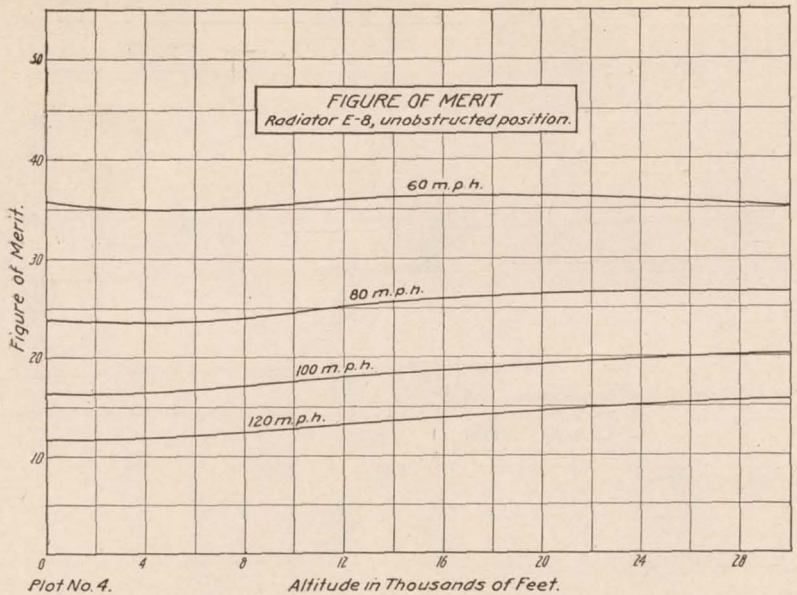
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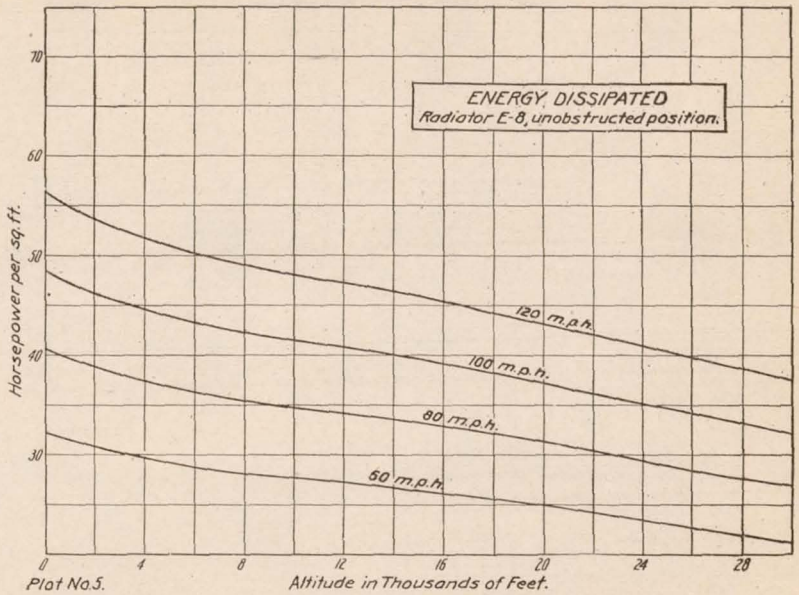
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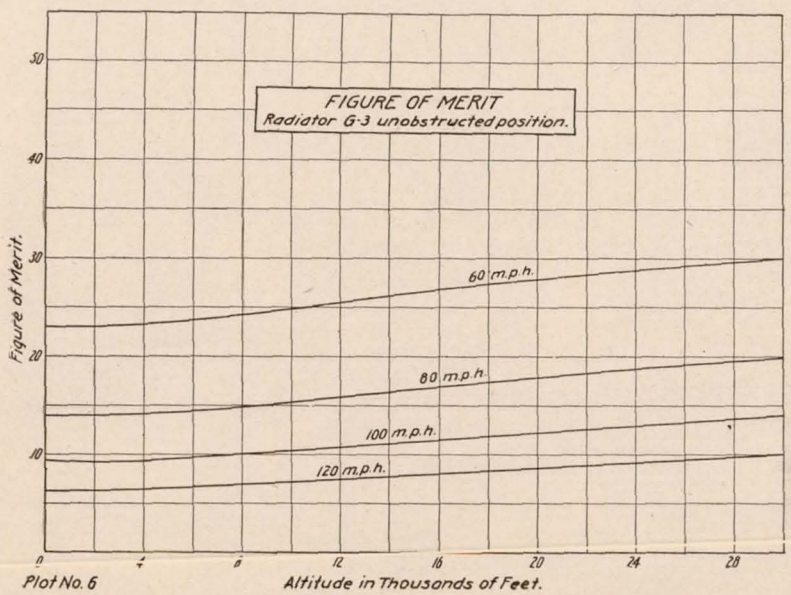
Plot No. 8



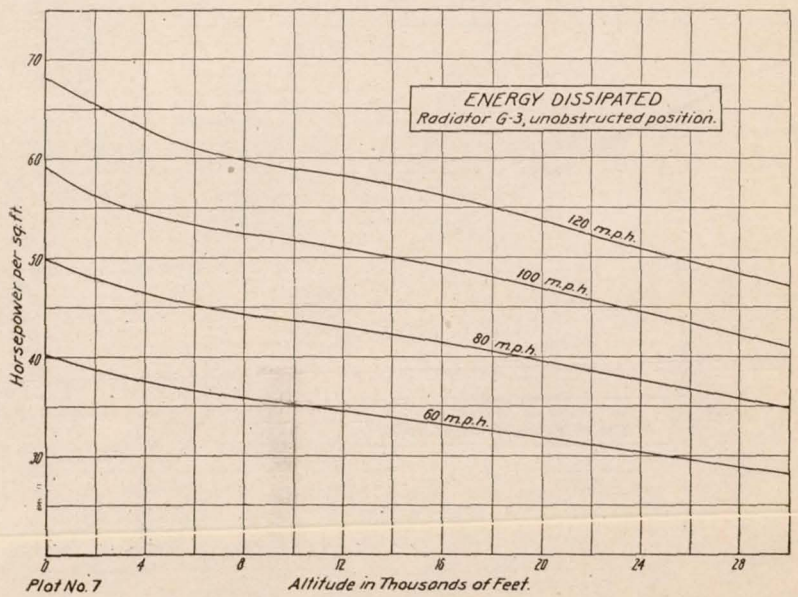
Plot No. 4.



Plot No. 5.



Plot No. 6



Plot No. 7

proposed empirical equations for the rate of heat transfer, in which the temperature difference occurred to a power slightly different from unity (in some cases as high as 1.2), but if the greatest value found were to be used, the difference between the result so obtained and that obtained using unity for the exponent, would be well within the range of uncertainty in atmospheric conditions at high altitudes. For the present purpose, therefore, the linear proportionality will be used.

4. Head resistance, for a given free air speed, is proportional to the density of the air. This fact is in general use by aerodynamic engineers, and while it has been verified by a part of the experimental work on which this report is based, it hardly requires to be proved here.

In order to give some idea of the atmospheric conditions that may be expected at altitudes, plots Nos. 1, 2, and 3 are included. These plots are based on data given by W. R. Gregg in the Monthly Weather Review, January, 1918. Plots 1 and 2 indicate mean summer, winter, and annual values of temperature and air density based upon observations at four stations situated in Indiana, Nebraska, South Dakota, and California. Plot No. 3 shows the boiling point of water corresponding to mean annual pressure at the same stations, only one line being plotted because the difference between annual and summer or winter means (1.5° at 25,000 feet, and less at lower altitudes) is so small that it may safely be neglected, in view of the uncertainties in all altitude conditions.

In order to make use of the data on atmospheric conditions, and in particular of the proportionalities mentioned above, it will be convenient to introduce the terms "density factor" and "temperature factor," and to define them as follows:

$$\text{Density factor} = \frac{\text{air density at altitude}}{\text{air density at ground}}$$

and

$$\text{Temperature factor} = \frac{\text{temperature difference existing at altitude}}{\text{temperature difference assumed at ground}}.$$

It will be noted that density and temperature difference "at ground" denote the assumed density and temperature difference to which the results of tests at ground have been reduced, and that the "factors" are not constants, but vary with altitude and with atmospheric conditions.

Then the actual values of density and temperature factors to be used in any particular computation will depend upon more or less arbitrary assumptions in regard to atmospheric conditions, and these assumptions will depend upon the conditions under which it is desired to study the performance of the radiator—whether for summer or winter flying, whether for mean or extreme conditions, etc. The temperature factor will also depend upon the limit set for maximum allowable water temperature.

It is now possible to express the properties of a radiator at an altitude in terms of its properties at the ground, and the density and temperature factors, as follows:

1. For a given free air speed, mass flow of air, being proportional to air density, is equal to the product of the mass flow at the ground by the density factor.

2. Energy dissipated *per 100° F.* temperature difference an altitude is the same as that dissipated per 100° F. at the ground *for the same mass flow of air.*

3. Energy actually dissipated at an altitude, being proportional to the temperature difference, is equal to the product of the energy dissipated per 100° F. by the temperature factor.

4. For a given free air speed, head resistance, being proportional to air density, is equal to the product of the head resistance at the ground by the density factor.

METHOD OF COMPUTATION.

The method of computing the performance at an altitude may be summarized as follows:

1. Choose an altitude and a free air speed.

2. Assume such conditions as will determine the values of the density and temperature factors.

3. To obtain energy dissipated, first find the mass flow of air at the ground and at the desired free air speed (from the results of ground tests), and multiply this value by the density factor to obtain the mass flow of air at the altitude.

4. Now, from the curve of energy dissipated against mass flow of air, given with the results of tests at the ground, obtain the energy dissipated per 100° F. for the mass flow computed for the altitude and multiply it by the temperature factor to obtain the energy actually dissipated at the altitude.

5. For head resistance, multiply the value at the ground and at the desired free air speed by the density factor to obtain the head resistance at the altitude.

6. Horsepower absorbed is computed as at the ground by adding to the head resistance the quotient obtained by dividing the weight per square foot frontal area of the radiator filled with water by the lift-drift ratio of the airplane, and multiplying this sum by the free air speed and the proper conversion factor.

7. Figure of merit, as at the ground, is the ratio of the energy dissipated to the horsepower absorbed.

EXAMPLE.

To estimate the performance of a radiator of the type E–8, described in Report No. 63, Part I, using results of ground tests as given in that report:

1. Assume, for illustration, an altitude of 10,000 feet and a speed of 120 miles per hour in level flight. Report No. 63, Part I, gives a curve showing energy dissipated per 100° F. temperature difference, in terms of mass flow of air, and the following quantities for ground conditions:

mass flow of air at 120 miles/hr. = 10.97 lb./sq. ft./sec.
head resistance at 120 miles/hr. = 12.5 lb./sq. ft.
weight of core and contained water = 14.15 lb./sq. ft.

2. Assume mean summer conditions of the atmosphere, and the requirement that the mean temperature of the water in the radiator shall be 30° F. below the boiling point. (These assumptions are, of course, arbitrary, and will vary with the conditions under which the plane is to be used.) Then the density factor at 10,000 feet will be the value of the "summer" curve of plot No. 2, divided by 0.0750, which is the assumed density at ground, or

$$\frac{0.0545}{0.0750}=0.727.$$

The temperature factor will be

$$\frac{(\text{boiling point}-30°)-(\text{summer mean})}{100}=\frac{194.2-30-50}{100}=1.142.$$

3. Mass flow of air at 10,000 feet = (mass flow at ground) (density factor) = (10.97) (0.727) = 7.98 lb./sq. ft./sec.

4. From the curve of energy dissipated against mass flow in Report No. 63, Part I, energy dissipated at 7.98 lb./sq. ft./sec. = 42.2 H. P. per sq. ft./100° F., but with the greater temperature difference, energy dissipated at the altitude = (42.2) (temperature factor) = (42.2) (1.142) = 48.2 H. P./sq. ft.

5. Head resistance at 10,000 feet = (head resistance at ground) (density factor) = (12.5) (0.727) = 9.09 lb./sq. ft.

6. Horsepower absorbed, if a lift-drift ratio of 5.4 is assumed, =

$$\left[(\text{head resistance})+\frac{(\text{weight filled})}{(\text{lift-drift ratio})}\right]\frac{(\text{free air speed})}{(375)}=\left[9.09+\frac{(14.15)}{(5.4)}\right]\frac{(120)}{(375)}=3.75 \text{ H. P./sq. ft.}$$

7. Figure of merit $=\frac{\text{energy dissipated}}{\text{horsepower absorbed}}=\frac{48.2}{3.75}=12.8.$

DESCRIPTION OF CURVES.

Plots Nos. 4 to 7 represent the properties of two types of radiator core at altitudes; plots Nos. 4 and 6, showing figure of merit, and plots Nos. 5 and 7, energy dissipated, in terms of altitude. The conditions and requirements assumed are mean summer density and temperature of air and a mean water temperature 30° F. below the boiling point. The computations are based upon data given in plots Nos. 1, 2, and 3.

Radiator E–8 is made of flat hollow plates set edgewise to the air stream, and its performance is typical of radiators adapted to use inunobstructed positions—that is, in such positions on the plane that the flow of air toward or away from the radiator is not obstructed by other parts of the plane.

Radiator G–3 is a type of high heat transfer and high head resistance, adapted to use only in obstructed positions. Its properties are computed, however, only for the condition of being placed in an unobstructed position, since the problem of determining head resistance in an obstructed position is too complex to be introduced into this report. (See Reports No. 59, General Analysis of the Radiator Problem, and 61, Part II, Resistance Due to Nose Radiator.)

The curves indicate that while heat transfer falls off with altitude, the figure of merit may increase slightly at the higher speeds. The general form of the curves is the same for both the type of core suitable for unobstructed positions and the type suitable for obstructed positions.

Plot No. 8, based on mean summer density, shows a typical relation of "density factor" to altitude; and since head resistance is proportional to density, this plot also shows the relation of head resistance at a given free air speed to altitude. No curve of "temperature factor" is shown, because so many different assumptions may be made in regard to atmospheric conditions and operating requirements that a single curve could hardly be called typical. "Temperature factor" can easily be computed for various assumptions from data given in the plots of temperature and boiling point against altitude.

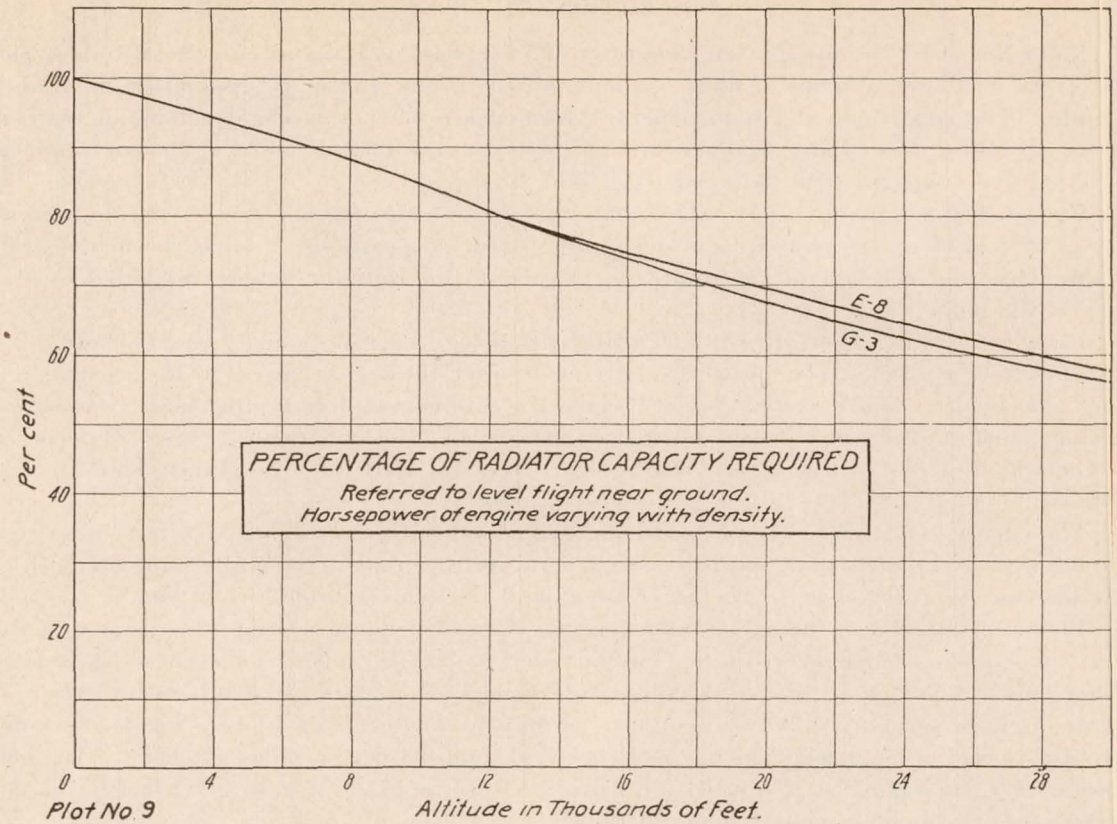
DEGREE OF MASKING REQUIRED AT ALTITUDES.

I. HORIZONTAL FLIGHT.

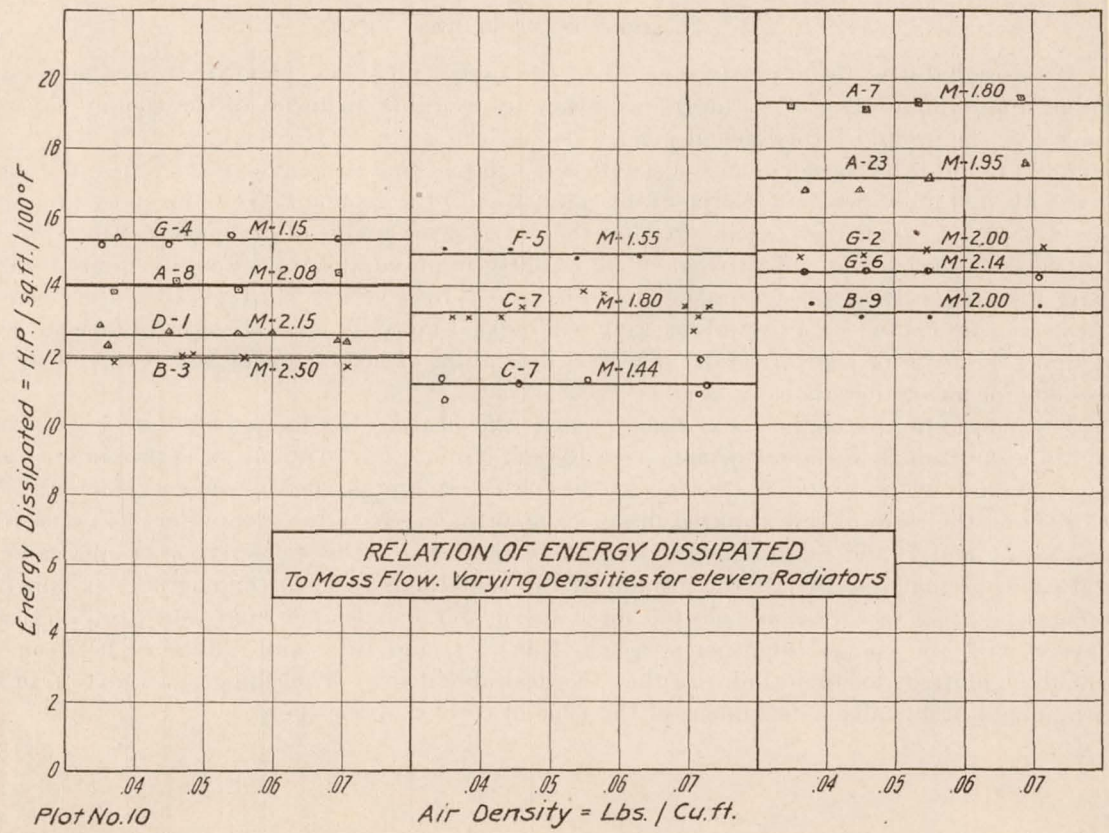
If the radiator is to be partly masked at the higher altitudes, plot No. 9 may be used to give an approximate idea of the degree of masking desirable, in terms of the cooling capacity required at the ground for *horizontal flight*.

Let a radiator be chosen of such a size that it will just cool the engine when flying at a given speed (say, 120 miles per hour) horizontally, and close to the ground. Now the energy required to be dissipated, divided by the energy that the radiator is capable of dissipating, will represent what may be termed the "effective area" of radiator required at an altitude, in square feet per square foot required at the ground. The adjective "effective" is used because the decrease in heat transfer caused by a partial masking will depend not only upon the area of face covered, but upon the form of shutter used. The real indication of heat transfer will be given by the mass flow of air, rather than by area.

The power of the engine, and consequently the heat to be dissipated, may be assumed roughly proportional to the air density (see Report No. 45, Part I), and an approximate value may be found by multiplying the energy dissipated at ground by the density factor. Plot No. 9 shows the ratio of this required dissipation to the capacity for dissipation, as taken from plots Nos. 5 and 7, and represents approximately the ratio of the "effective area" desirable at an altitude to that required at the ground, if the radiator is to keep the engine at a constant temperature. These curves are plotted for a speed of 120 miles per hour, but are practically identical with the curves for other speeds. This fact, and the small difference between the two curves plotted, seems to indicate that the desirable degree of masking is a function of the altitude, and practically independent of the type of core or of the speed.



Plot No. 9



Plot No. 10

II. CHANGE FROM CLIMBING TO HORIZONTAL FLIGHT.

When the plane changes from maximum climb to horizontal flight, its speed will be greatly increased (for some types of planes, about doubled), and this increase in speed will involve a proportional increase in mass flow of air, and a corresponding (though not proportional) increase in heat transfer. This consideration alone would require a degree of masking that would in some cases approach 50 per cent of the effectiveness of the radiator at the altitude, but it has not been included in the computations for plot No. 9 because of a wide range of its variation with different planes and their different uses. If the relation is known between the maximum climbing speed and the horizontal speed when using the same engine power, then the mass flow of air and the corresponding heat transfer can be determined from the results of tests at the ground, and the degree of masking that is desirable can be found from the two rates of heat transfer.

It may be well to note that no account has been taken of additional cooling from the surface of the engine itself or from connecting pipes, caused by the lowering of the air temperature; and again let it be emphasized that mass flow of air gives the real measure of what has been termed "effective area."

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REPORT No. 63

RESULTS OF TESTS ON RADIATORS FOR AIRCRAFT ENGINES

Part I.—HEAT DISSIPATION AND OTHER PROPERTIES OF RADIATORS

By H. C. DICKINSON, W. S. JAMES, and R. V. KLEINSCHMIDT

Part II.—WATER FLOW THROUGH RADIATOR CORES

By W. S. JAMES

Bureau of Standards, Washington, D. C.

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REPORT No. 63.

PART I.

HEAT DISSIPATION AND OTHER PROPERTIES OF RADIATORS.

By H. C. Dickinson, W. S. James, and R. V. Kleinschmidt.

INTRODUCTION.

The present report is the fourth of a series of reports on airplane radiators, incorporating the results of experimental work at the Bureau of Standards under the joint auspices of that Bureau, the Aviation Departments of the Army, and the National Advisory Committee for Aeronautics. The first three are the following:

Technical Report No. 43, Synopsis of Aeronautic Radiator Investigations for the years 1917–1918;

Technical Report No. 59, General Analysis of the Airplane Radiator Problem; and

Technical Report No. 60, General Discussion of Test Methods for Radiators.

These reports contain a discussion of the technical terms used and briefly defined in the present report, and a discussion of the methods used in obtaining the data on which the present report is based.

PURPOSE.

The purpose of this report is to present the results of tests on 56 types of core in a form convenient for use in the study of the performance of and possible improvements in existing designs. Working rules are given by which the data contained in the report may be used, and the most obvious conclusions as to the behavior of cores are summarized.

DEFINITIONS OF TERMS.

(For a complete discussion of the terms and their significance, see the "Analysis," Technical Report No. 59.)

I. CHARACTERISTICS WHICH DESCRIBE A TYPE OF CORE.

These characteristics are given in Table I, and a few of the most important are included on each curve sheet.

Metal is designated as brass or copper without attempting to give exact composition. The thickness is approximate to 0.001 inch.

Dimensions of core.—Length is measured in the general direction of the water flow; depth, in the general direction of air flow; and width perpendicular to these two.

Dimensions of water tubes.—Length (in the direction of water flow) is expressed in inches per foot length of core; depth is measured in the same direction as depth of core; and width is the thickness of the stream of water.

Cooling surface is regarded as direct only when backed by flowing water. Indirect surface includes fins, spacers, and surface backed by stagnant water.

Per cent free area is the cross-sectional area of the air tubes in per cent of the frontal area.

All characteristics are given for a section of core 1 foot square.

II. PROPERTIES THAT DESCRIBE THE PERFORMANCE OF A CORE.

The properties of a core are obtained primarily for the purpose of comparing cores. It must be remembered that the properties of a complete radiator on a plane depend, not only upon the properties of the core but on the location of the radiator on the plane. This is especially true of head resistance and the properties involving it. (The method of estimating the probable performance of a radiator from the properties of its core is given under "Use of the data in designing a radiator," below.)

Mass flow of air through the core is expressed in pounds per second per square foot of frontal area. When a core is supported in a free air stream, the flow of air through it is proportional to the free air speed (for ordinary types of core).

The mass flow constant is the ratio between the mass flow through the core, and the mass of air flowing through a square foot of area normal to the direction of flow in the undisturbed air stream. For some purposes it is more convenient to use a "mass flow factor" which is the factor by which free air speed in miles per hour must be multiplied to obtain mass flow.

Energy dissipated or heat transfer is expressed in horse power per square foot of frontal area, for a difference of 100° F. between the temperature of the air entering the radiator and the mean of the temperature of the entering and leaving water.

Head resistance of the core is the force required to push it through the air, and is expressed in pounds per square foot of frontal area.

Head resistance constant is the factor by which the square of the free air speed in miles per hour must be multiplied to obtain head resistance in pounds per square foot.

Horsepower absorbed is computed by adding to the head resistance the quotient obtained by dividing the weight of core and contained water (in pounds per square foot front) by the lift-drift ratio of the airplane, and multiplying the sum by the speed of the plane and by a conversion factor.

As the lift-drift ratio varies between different planes and varies even more widely between climbing and level flight, it is very important to consider, in the selection of a core, the relative importance of climbing speed and top speed. The value 5.4 is used throughout this report as a good average for planes and gives equal weight to rate of climb and top speed. If rate of climb is of prime importance the value should be as low as 3, while if speed on the level is the most important a value as high as 10 may be used.

Figure of merit is the ratio of the energy dissipated in horsepower to the horsepower absorbed.

Pressure necessary to produce water flow is of importance in determining the maximum flow possible through a given type of core.

CONDITIONS UNDER WHICH THE CORE OPERATES.

As the properties of a core vary with the conditions under which it is used, it is necessary to express the results of tests in terms of certain definite conditions adopted as standard. The conditions adopted in this work are:

1. *Water flow* must be high enough to insure turbulent flow. For most types of core this means that it must be above about 2 gallons per minute per inch of core depth per foot width of core.

2. *Temperature difference* (between entering air and mean water temperature) of 100° F. is used in computing the heat transfer and figure of merit as given.

3. *Air density* is taken as 0.0750 pounds per cubic foot. All results given in this report are reduced to these conditions.

Since one of the most important conditions affecting radiator performance is the mass flow of air through the core, the properties of the cores have been expressed in terms of mass flow.

The effects of variation from the conditions adopted as standard are treated in detail in separate reports, but are mentioned below in a form for use in design.

GENERAL FACTS DEDUCED FROM THE RESULTS OF EXPERIMENTS.

General statements deduced from the results of the experiments, together with a few of the most important conclusions from other reports, are as follows:

HEAT TRANSFER.

1. Heat transfer is a function of *mass flow of air*, independent of density. (See Technical Report No. 62.)

2. Heat transfer is roughly proportional to *mass flow* for a core having only *direct cooling surface*. When there is a considerable amount of indirect cooling surface the heat transfer increases less rapidly than mass flow at high air speeds.

3. Heat transfer is proportional to the *temperature difference* mentioned above.

4. Heat transfer is not greatly affected by the *rate of water flow* provided the rate is above 2 gallons per minute per inch of core depth per foot width of core. It should be noted, however, that this is true only when the mean water temperature is regarded as constant. (See below, "Use of data in the design of radiator: Rate of water flow.")

5. Heat transfer from *direct* cooling surface is not appreciably affected by the *composition of the metal.* When fins and other indirect cooling surface are used the thermal conductivity of the metal is important.

6. Heat transfer is somewhat increased, but at the expense of a large increase in head resistance, by spirals or other forms of passages which increase the turbulence of the air stream. Heat transfer is greater for smooth than for rough tube walls, for, if the surface is rough, it will be covered with a layer of more or less stagnant fluid.

HEAD RESISTANCE.

1. Head resistance for any particular core varies approximately as the square of the *free air speed.* In most cases the exponent is slightly less than 2. Radiator E–4 is an exception to this rule. This radiator exhibits resonance effect which causes it to whistle in an air stream having a velocity of more than about 30 miles per hour, and cause head resistance curve to show irregularities in the region where whistling starts.

2. The head resistance of a core appears to be closely related to its mass flow constant so that, in general, anything which tends to cut down the flow of air through the core will cause a considerable increase in head resistance. (See plot 1.)

3. Head resistance varies directly as the *air density* for a given free air speed, and inversely as the density for a given mass flow. (See Technical Report No. 62.)

4. Head resistance is considerably increased by projections, indentations, or holes in the air tube walls.

5. Head resistance per square foot is not appreciably affected by the *size of the core* within the limits used, viz, 8 by 8 inches to 16 by 16 inches and 12 by 24 inches. (See Technical Report No. 61, Part I.)

MASS FLOW OF AIR.

Mass flow of air is directly proportional to *free air speed* for most types of core. The cores E–4 and G–4 are exceptions.

USE OF THE DATA IN THE DESIGN OF A RADIATOR.

CHOICE OF A POSITION.

The first step in the design of a radiator is the choice of a position on the airplane. The possible positions may be divided into two classes:

1. Unobstructed positions, i. e., those in which the flow of air through and around the radiator is not obstructed by other portions of the plane.

2. Obstructed positions, such as the nose of the fuselage, a position within the fuselage, and in the plane of the wing.

It has been shown in Technical Report No. 61, and also in reports of work done both in Great Britain and in France, that an obstructed position involves a very large absorption of power, so that from the viewpoint of power absorbed for a given heat transfer, the unobstructed position is far preferable to the obstructed. Tests on a model have shown that the resistance of a fuselage fitted with a nose radiator is from two to three times the resistance of the same fuselage with a stream-line nose, and that the increase in resistance due to the substitution of a radiator for the stream-line nose is greater than the increase that would be caused by using a radiator of the same core construction and the same cooling capacity in an unobstructed position.

SELECTION OF A TYPE OF CORE.

In an unobstructed position the head resistance and consequently also the figure of merit of the *core* will be closely related to these properties of the *complete radiator*, so that in this case the

core must have a high figure of merit at the free air speed at which it is used. The most compact construction consistent with this fundamental requirement is desirable. In order to obtain a high figure of merit the core should have smooth, straight air passages, easy entrances and exits for the air, and a large per cent free area. With these factors carefully attended to the figure of merit of cores increases with depth up to 20 times the diameter of the air tubes, which is as far as experiments have been made. Even greater depth may be of advantage in obtaining compactness.

By far the most satisfactory radiator for use in unobstructed positions seems to be one of thin flat plates, not over $\frac{1}{16}$ inch thick, and spaced $\frac{1}{2}$ inch on centers. The plates should be at least 12 inches in depth. The chief defect of this type of construction is mechanical weakness. (See cores E–6, E–7, and E–8.)

Of radiators now in commercial use in this country that have been tested, Nos. A–23, A–13, A–20, A–19, and A–7 are best suited to use in unobstructed positions, but they are decidedly inferior to the flat plate type at high air speeds.

For use in obstructed positions the selection of a core is more difficult, but in general high heat transfer at low air speeds is desirable. Indirect cooling surface may be of advantage if it is made of copper, crimped from the water tube walls, and well soldered to them at all possible places.

Among the cores tested, Nos. A–7, A–20, G–3, A–2, G–4, and B–8 are best suited for obstructed positions. It should be noted that for use in the wing, a high head resistance of the core is not a disadvantage, and it is possible that a core such as F–4, which has considerable mechanical strength and a low water resistance, might be used.

With this possible exception, the fin and tube type is unsuited for use in any position, its high head resistance and small amount of direct cooling surface making its efficiency very low.

SIZE OF CORE.

Having selected a type of core for the desired location, the computation of size required is relatively simple. In the case of a radiator for an unobstructed position, the heat transfer can be determined directly from the curves if the desired best climbing speed of the plane and the air temperature are known. The effect of propeller slip must be estimated and allowed for. The energy to be dissipated should be determined if possible in any particular case, but is usually about equal to the brake horsepower of the engine. Then the ratio of the energy to be dissipated to the energy dissipated per square foot frontal area of core will give the frontal area required. From the weight and head resistance the effect of the radiator on the aerodynamical properties of the plane can be determined.

In the case of a radiator placed in the nose of the fuselage, until better data are available, the mass flow of air in pounds per second per square foot may be considered numerically as between 0.04 and 0.07 times the speed of the plane in miles per hour, depending on the amount of cowling and the masking effect of the propeller. From this the mass flow can be estimated, and the energy dissipated per square foot frontal area is determined from the plots, using the mass flow scale.

The mass flow for a wing radiator depends upon the angle of incidence, but is probably not over 0.01 times the plane speed in M. P. H., even at the best climbing angle. The tubes are in this case presented to the air at an angle which probably increases the heat transfer considerably.

POWER ABSORBED.

Power absorbed can be computed readily only in the case of a radiator in an unobstructed position. The actual force on the radiator core when in an obstructed position may be computed from the curves of head resistance against mass flow, but the uncertain effect on the properties of the fuselage is of far greater importance. For obstructed radiators, the power absorbed as computed represents only the minimum possible absorption.

RATE OF WATER FLOW.

Although the energy dissipated as given in the curves is practically constant for rates of water flow above about 2 gallons per minute per foot width per inch depth of core, the allowable mean temperature increases slightly with increased water velocity, since it is the temperature of the entering water that must be kept at a certain point below boiling. With a flow of ¼ gallon per minute per horsepower dissipated a temperature difference of about 20° F. is obtained, or the mean water temperature in the radiator is 10° F. below the entering water temperature. If the flow is increased to ½ gallon per minute the temperature difference will be 10° and the mean temperature may be 5° higher than before. A further increase in water flow could not give more than 5° further increase and would probably be at the cost of an excessive loss of power in the pump. A flow of ½ gallon per minute per horsepower dissipated may be regarded as desirable, while with radiators that are relatively long and narrow a decrease of flow to ¼ gallon per minute per horsepower dissipated may be necessary.

PRESSURE NECESSARY TO PRODUCE WATER FLOW.

The pressure which is available to produce the water flow is usually the difference between the vapor pressure of the water leaving the radiator and atmospheric pressure. As this pressure difference may be only about 5 pounds per square inch, the resistance of the core to water flow may limit the possible flow seriously unless care is taken to make the core as wide as possible.

The water resistance of a core seems to depend largely on the care used in manufacture and on the form of the water tube entrances and exits. In the light of tests made, it seems that it would be well to include a test for pressure necessary to produce water flow in acceptance specifications for complete radiators, as slight variations in manufacture affect water resistance greatly. In Part II of this report are given the results of some tests on water resistance.

DESCRIPTION OF TABLES AND CURVES.

In order to indicate the degree of reliability of the results shown, actual observations are indicated on the plots by circled points, and at the end of this report is a brief statement showing the means used in obtaining results for the cases where "observed" points are not shown.

Table I contains the characteristics of cores as noted above and sketches showing the form of air and water passages. This table includes certain special types of core on which complete tests have not been made and which are accordingly not included in this report. The special properties of such cores will be made the subjects of separate reports.

Table II lists the properties of the cores at mass flows of air of 2, 4, 6, and 8 pounds per square foot per second, in order to allow ready comparison between them. It also includes the heat transfer in B. t. u. per minute per square foot of frontal area of core, and in horsepower and in B. t. u. per minute per square foot of cooling surface.

Table III lists the same properties as Table II at free air speeds of 30, 60, 90, and 120 miles per hour. In addition, it gives the mass flow (at "standard" density) corresponding to these free air speeds, and a "grade" for the radiator, grade A denoting very good performance and grade E very poor performance, among the cores tested. This table is directly applicable only to radiators in unobstructed positions.

Table IV gives constants of empirical equations for heat transfer, head resistance, and mass flow, for cores in unobstructed positions.

Plot 1 is an approximate empirical relation between the proportionality factors for head resistance and mass flow.

The remaining plots show the properties of the cores in terms of mass flow of air, with the corresponding free air speeds (for unobstructed positions) indicated by a scale added at the top of the sheet. For the core E–4, the mass flow is not a linear function of the free air speed, and a separate plot shows the properties in terms of free air speed. For the core G–4, the relation of mass flow to free air speed is linear above 15 miles per hour, but not below that speed, which fact accounts for what would appear to be an error in marking the free air speed scale of plot 58.

NOTE ON SOURCES OF DATA.

Because of the undesirability of removing the headers from all specimens so that head resistance could be measured directly, and because certain mechanically weak specimens became damaged before complete tests had been made, a part of the data was obtained not from direct measurement but by the methods described below.

Mass flow of air was measured in terms of free air speed on all specimens except E–7, and in this case was estimated by interpolation between the values for E–6 and E–8.

Heat transfer was measured in terms of mass flow of air on all types except the following:

E–4, estimated by interpolation between the values for two similar types of the same depth, but different spacings.

E–6, E–7, determined by correction from preliminary tests made before the apparatus was put in final form.

F–5, estimated from results obtained on a similar type of slightly different depth.

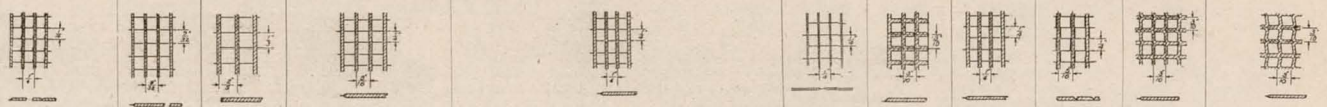
Head resistance was measured directly on half of the cores included in this report, and on a number of others not included, and the proportionality factor for head resistance was plotted against that for mass flow, in the cases of about 40 types having smooth straight air passages. The resulting points fell very near a single line, which is shown in plot 1, and this plot was used to determine head resistance from a measured mass flow factor for other types with smooth straight air passages. Values thus obtained are probably good within about 5 per cent.

The cores A–19 to A–22 and G–2 could not be treated in this way because points for similar types did not lie on the curve of plot 1, and in these cases the head resistance was estimated by comparison with other similar types and with the plot.

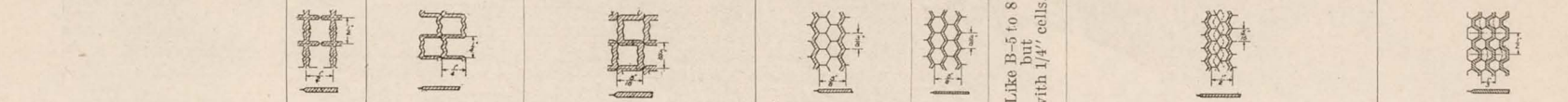
Head resistance of type C–2b was determined by interpolation with respect to mass flow between values for C–2 and C–2a.

Head resistance of types E–6, 7, and 8 was determined from the results of a fairly comprehensive set of tests on the head resistance of flat plate radiators of various depths and spacings.

TABLE I.—*Characteristics of radiators.*

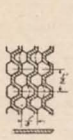
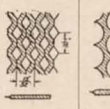
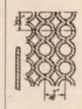
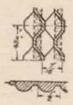
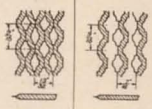
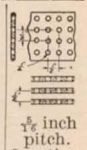


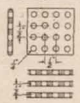
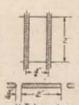
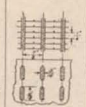
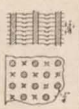
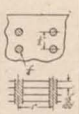
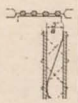
	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10	A-11	A-12	A-13	A-14	A-15	A-16	A-17
Number																	
Depth, inches	3	3 1/8	2 3/8	2 7/8	3	4	4 7/8	2 3/8	2 5/8	3 7/8	4 3/4	3 1/2	3 3/8	3 7/8	3	3	4
Metal:																	
Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Brass	Copper	Brass	Brass	Brass.
Fins				Copper										Copper			
Thickness of metal, inches	0.005	0.005	0.005	0.006	0.010	0.010	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.006		0.004	0.004
Weight, lbs/ft.² front:																	
Empty	13.7	18.3	9.6	11.6	10.3	13.9	17.1	8.2	10.0	13.4	15.1	14.6	11.3	18.2	12.1	12.1	15.8
Water content	2.1	3.1	1.5	2.1	3.1	3.4	7.2	2.6	3.2	4.9	2.9	3.0	3.2	3.5	3.0	2.4	3.0
Filled	15.8	21.4	11.1	13.7	13.4	17.3	24.3	10.8	13.2	18.3	18.0	17.6	14.5	21.7	15.1	14.5	18.8
Per cent free area	65.5	65.7	79.6	76.5	68.0	74.9	64.2	66.2	66.8	67.8	65.6	69.2	70.4	72.1	53.0	69.8	72.1
Cooling surface, ft.²/ft.² front	39.3	51.9	30.3	28.6	36.6	49.1	62.6	30.3	37.3	51.1	61.7	39.4	43.9	46.3	35.3	34.6	47.1
Per cent direct cooling surface	44.0	44.0	46.6	44.1	47.3	46.6	52.2	47.8	47.7	54.2	48.3	40.6	50.3	48.6	42.7	43.9	43.5
Water tubes:																	
Length, in./ft. of core	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Width, inches	.045	.0471	.039	.0581	.061	.054	.078	.0641	.066		.033	.063	.0518	.054	.0545	.051	.048
Depth, inches	2.37	3.15	2.08	2.75	2.74	3.60	4.45	2.06	2.49		4.45	3.11	3.00	3.80	2.60	2.68	3.63
Number per foot	48	48	42	30	42	40	48	45	45		45	36	47	37	49	40	40
Area normal to flow, ft.²/ft	.0340	.0495	.0237	.0333	.0491	.0541	.1156	.0414	.0510		.0916	.0486	.0507	.0565	.0482	.0378	.0480
Hydraulic radius inches	.0211	.023	.019	.0286	.031	.027	.038	.0312	.032		.016	.0308	.0255	.0285	.0364	.0249	.024
Air tubes:																	
Hydraulic radius, inches	.050	.050	.063	.078	.056	.061	.050	.052	.052	.052	.051	.063	.055	.061	.047	.062	.062
Ratio, length÷hyd. rad	58.8	78.0	38.1	37.1	53.2	65.0	97.2	45.4	54.8	75.0	92.8	55.7	61.1	63.8	63.4	48.6	64.6
Number of plot	2	3	4	5	6	7	8	9	10			11	12	13	14	15	16



	A-18	A-19	A-20	A-21	A-22	A-23	B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10	B-11
Number																	
Depth, inches	4	3	5	3	4	5	2 1/2	4	3	3 1/4	2	3 1/4	4	5 1/4	3 1/2	2 1/2	3
Metal:																	
Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Copper	Copper	Brass	Brass	Brass	Brass	Copper	Brass	Brass	Brass	Brass.
Fins																	
Thickness of metal, inches	0.004	0.005	0.005	0.009	0.005	0.005	0.006	0.006	0.005	0.005	0.004	0.005	0.005	0.005	0.004	0.005	0.005
Weight, lbs./ft.² front.																	
Empty	8.9	13.8	22.9	9.3	12.5	15.6	6.70	10.7	9.3	12.3	5.5	8.8	10.7	13.9	10.4	7.4	8.9
Water content	2.9	3.1	5.4	3.5	4.3	6.3	1.06	.63	2.0	2.1	1.0	1.7	2.3	4.2	4.0	3.1	3.9
Filled	11.8	16.9	28.3	12.8	16.8	21.9	7.76	11.3	11.3	14.4	6.5	10.5	13.0	18.1	14.4	10.5	12.8
Per cent free area	83.0	67.7	66.9	65.6	66.6	68.5	83.6	88.0	79.6	72.7	81.2	79.0	77.0	73.3	65.1	65.1	65.1
Cooling surface, ft.²/ft.² front	27.6	40.3	66.8	31.5	42.5	54.5	21.6	36.1	26.8	37.2	23 8	37.9	45.8	56.1	36.2	25.5	30.4
Per cent direct cooling surface	46.7	86.9	92.1	86	91	91.8	37.5	34.6	58.6	28.0	27.8	26.7	27.7	30.3	66.5	62.7	64.8
Water tubes:																	
Length, in./ft. of core	12.0	24.0	24.0	24.0	24.0	24.0	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	14.8	14.8	14.8
Width, inches	.089	.028	.028	.041	.0348	.0402	.056	.019	.043	.051	.0524	.057	.062	.0822	.0788	.079	.082
Depth, inches	3.65	2.64	4.63	2.59	3.67	4.64	2.21	3.78	2.68	2.88	1.73	2.68	3.40	4.84	3.06	2.03	2.50
Number per foot	21	48	48	39	39	39	17	18	30	29	22	22	22	21	31	36	36
Area normal to flow, ft.²/ft	.0459	.0249	.0435	.0284	.0348	.0505	.0148	.0087	.0276	.0295	.0139	.0232	.0315	.0597	.0521	.0402	.0511
Hydraulic radius, inches	.042	.014	.014	.0199	.0178	.0199	.0270	.0091	.0245	.025	.026	.028	.0298	.040	.0386	.038	.0396
Air tubes:																	
Hydraulic radius, inches		.051	.050	.063	.063	.064	.088	.089	.090	.053	.071	.070	.070	.069			
Ratio, length÷hyd. rad		58.9	100	47.2	63.4	78.1	28.6	45.2		61.9	28.9	46.9	57.2	76.2			
Number of plot	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33

TABLE I.—*Characteristics of radiators*—Continued.

				Like C-2 with 8 inch twisted "swirlers" in cells.	Like C-2 with 2 inch swirler in one end of cells.	Like C-2 but with ⅛ inch hexagon air-tubes.	Like C-3 with 8 inch twisted swirlers.							$\frac{5}{16}$ inch pitch. 2 sections deep.
Number	B-12	B-13	C-1	C-2	C-2a	C-2b	C-3	C-3a	C-4	C-5	C-6	C-7	D-1	D-2	D-3	D-4	E-1
Depth.....inches	$3\frac{1}{4}$	4	$3\frac{3}{8}$	$8\frac{3}{8}$	$8\frac{1}{4}$	$8\frac{3}{8}$	$8\frac{1}{4}$	$8\frac{1}{4}$	$2\frac{7}{8}$	$3\frac{1}{2}$	3	$3\frac{1}{2}$	$2\frac{5}{8}$	8	$3\frac{1}{2}$	$3\frac{1}{2}$	$4\frac{3}{4}$
Metal:																	
Water tubes	Brass	Brass	Brass	Brass	Brass	Brass	Copper	Copper	Brass	Copper	Copper	Copper	Copper	Brass	Brass	Brass	Copper.
Fins								Brass					Brass				
Thickness of metal.....inches	0.005	0.005	0.005	0.004	[1].005 [2].009	0.005	0.006	0.005	0.005	0.005	0.006	0.007	0.010	0.01	0.011	0.011	0.004
Weight, lbs./ft.² front:																	
Empty	9.6	11.9	9.6	15.7	19.2	16.7			9.2	18.3	9.1	10.5	8.5	26.9	12.8	9.1	13.6
Water content	3.9	5.4	6.6	11.5	10.7	7.6	6.2	5.0	3.9	7.1	3.6	4.1	2.2	7.2	6.2	3.9	5.2
Filled	13.5	17.3	16.2	27.2	29.9	24.3			13.1	25.4	12.7	14.6	10.7	34.1	19.0	13.0	18.8
Per cent free area	65.1	65.1	51.9	60.4	63.2	62.5	81.6	83.9	62.6	49.5	70.9	70.8	75.8	68.7			72.2
Cooling surface.....ft.²/ft.² front	34.0	41.6	32.1	48.3	76.6	56.7	51.5	64.0	32.0	35	30.4	32.5	23.7	84.1	32.6	42.0	25.0
Per cent direct cooling surface	66.2	67.6	94.2	87.2	56.3	75.9	57.3	46.9	57.2	100	46.4	46.4	46.8	44.9	83.1	42.1	89.6
Water tubes:																	
Length.....in./ft. of core	14.8	14.8	14.9	13.9	13.9	13.9	13.9	13.9	13.8	17.2	15.8	16.8	12.0	12.0			12.0
Width.....inches	.072	.079	.071	.118	.111	.118	.0781	.0695	.073	.060	.068	.088	.074	.0925		.0873	.073
Depth.....inches	2.86	3.56	3.18	7.42	7.40	7.46	7.18	7.21	2.50	3.42	2.52	3.06	2.20	7.50	2.94	2.90	2.26
Number per foot	36	36	57	25	26	26	22	20	43	55	27	25	29	24	58	29	76
Area normal to flow...ft.²/ft.	.0512	.0705	.089	.161	.148	.1575	.0856	.0699	.0546	.079	.0320	.0468	.0348	.1155		.0510	.0824
Hydraulic radius.....inches	.035	.040	.0345	.062	.055	.062	.039	.0345	.0355	.030	.033	.0427	.038	.0459			.037
Air tubes:																	
Hydraulic radius.....inches			.055	.107					.062		.074						
Ratio, length÷hyd. rad			61.5	77.9					47.1		40.7						
umber of plot	34	35	36	37	38	39			40	41	42	43	44	45	46	47	

										Like F-1 but fins ½ inch apart.		inch round tubes with ¾ inch crimped helical, ¼ inch pitch, staggered, fins almost touching.			*Front.*	Two sections like G-2 built together back to back.	
	$\frac{5}{16}$ inch pitch. 3 sect. deep.	$\frac{5}{16}$ inch pitch. 4 sect. deep.	½ inch pitch. 4 sect. deep.	$\frac{5}{8}$ inch pitch. 4 sect. deep.	¼ inch pitch.	⅜ inch pitch.	½ inch pitch.										
Number	E-2	E-3	E-4	E-5	E-6	E-7	E-8	E-9	F-1	F-2	F-3	F-4	F-5	G-1	G-2	G-3	G-4
Depth.....inches	$7\frac{3}{8}$	$9\frac{1}{4}$	$9\frac{1}{2}$	$9\frac{3}{8}$	$9\frac{3}{4}$	$9\frac{1}{4}$	$9\frac{1}{4}$	$23\frac{1}{2}$	$2\frac{1}{4}$	$2\frac{1}{4}$	$4\frac{1}{8}$	$3\frac{5}{8}$	$3\frac{1}{8}$	$2\frac{3}{8}$	$1\frac{1}{4}$	$3\frac{3}{8}$	4
Metal:																	
Water tubes	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Copper	Brass	Copper	Copper	Copper.
Fins											Brass		Brass				
Thickness of metal.....inches	0.005	0.005	0.005	0.005	0.004	0.004	0.004		0.011	0.006	0.004	0.004	0.010		0.005	0.006	0.005
Weight, lbs./ft.² front:																	
Empty	20.4	27.2	16.3	14.2	16.8	11.2	9.2	[3] 39.0					7.6	8.7	5.5	11.0	13.0
Water content	7.9	10.9	6.4	5.7	9.3	6.5	5.0	9.8	1.7	1.5	1.5	2.8	1.3	1.4	1.5	2.9	6.9
Filled	28.3	38.1	22.7	19.9	26.1	17.7	14.2	[3] 48.8					8.9	10.1	7.0	13.9	19.9
Per cent free area	71.5	71.4		88	75.0	83.3	87.5	85	76.5	74.4					74.4	72	41.2
Cooling surface.....ft.²/ft.²front	37.2	49.6	29.5	25.5	78.5	52.3	39.2	68.9	15.9	25.0	49.7	43.0	34.5	27.2	22.4	44.7	52.2
Per cent direct cooling surface	93.0	94.8	94.6	97.3	100	100	100	89.5	37.9	23.8	14.6	18.2	12.3	23.2	43.2	42.9	84.9
Water tubes:																	
Length.....in./ft. of core	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	13.1	13.1	12.0
Width.....inches	.073	.073	.073	.073	.0525	.0525	.0525	.062					.235		.0723	.069	.127
Depth.....inches	2.26	2.26	2.26	2.25	9.74	9.74	9.74	1.86					.235	1.84	1.30	1.30	3.33
Number per foot	114	152	60	80	48	32	24	176	42	42	90	72	72	29	34	68	38
Area normal to flow...ft.²/ft.	.1264	.174	.174	.174	.170	.113	.085	.1366	.0273	.0249	.0237		.0216		.0222	.0212	.1115
Hydraulic radius.....inches	.037	.037	.037	.037	.0108	.0108	.0108	.0142	.068	.068	.059	.085	.059		.034	.033	.061
Air tubes:																	
Hydraulic radius.....inches					.0938	.156	.218										
Ratio, length÷hyd. rad					104	62.5	44.7										
Number of plot			48 & 49		50	51	52	53					54	55	56	57	58

[1] Tubes. [2] Fins. [3] Estimated.

TABLE II.—*Radiator performance in terms of mass flow of air.*

All values except energy dissipated per square foot cooling surface are reduced to 1 square foot of frontal area. Head resistance, horsepower absorbed, and figure of merit apply to radiator in an unobstructed position.

Radiator.	Air flow.	Energy dissipated per square foot—				Head resistance.	H. P. absorbed.	Figure of merit.
		Front.		Surface.				
		H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
A-1	2	19.6	831	0.50	21.1	1.2	0.3	70.5
	4	32.8	1,390	.83	35.4	4.7	1.1	31.3
	6	44.3	1,880	1.13	47.8	10.5	2.9	16.1
	8	54.6	2.320	1.39	59.0	18.8	6.1	9.1
A-2	2	20.6	874	.40	16.8	1.3	.4	55.1
	4	36.8	1,560	.71	30.0	5.3	1.3	28.2
	6	51.2	2,170	.99	41.8	11.7	3.4	15.2
	8	65.2	2,760	1.26	53.1	21.0	7.2	9.2
A-3	2	12.3	522	.41	17.2	.6	.1	79.0
	4	19.9	844	.66	27.8	2.1	.5	41.3
	6	26.5	1,120	.87	37.0	4.7	1.2	22.7
	8	32.5	1,380	1.07	45.5	8.4	2.4	13.4
A-4	2	12.8	543	.45	19.0	.8	.2	63 3
	4	22.2	942	.78	32.9	3.1	.7	32.4
	6	30.4	1,290	1.16	45.1	6.9	1.8	17.6
	8	37.8	1,600	1.32	56.0	12.4	3.6	10.4
A-5	2	16.1	683	.44	18.7	1.1	.3	68.8
	4	27.4	1,160	.75	31.7	4.1	.9	31.7
	6	37.7	1,600	1.00	43.7	9.1	2.3	16.3
	8	47.3	2,010	1.29	54.9	16.2	5.0	9.6
A-6	2	17.8	755	.36	15.4	1.1	.3	61.0
	4	31.1	1,320	.63	26.9	4.5	1.1	29.4
	6	42.7	1,810	.87	36.9	10.1	2.7	15.7
	8	53.7	2,280	1.09	46.4	18.1	5.8	9.2
A-7	2	25.1	1,060	.40	16.9	1.4	.4	58.0
	4	42.8	1,820	.68	29.1	5.6	1.5	29.4
	6	57.7	2,450	.92	39.2	12.3	3.7	15.7
	8	71.3	3,020	1.14	48.2	21.9	7.6	9.4
A-8	2	13.3	564	.44	18.6	1.1	.2	64.0
	4	22.7	963	.75	31.8	4.1	.8	28.5
	6	31.5	1,340	1.04	44.2	9.1	2 2	14.4
	8	39.7	1,680	1.31	55.5	15.7	4.7	8.7
A-9	2	16.8	712	.45	19.1	1.2	.3	67.8
	4	29.7	1.260	.80	33.8	4.7	1.0	30.2
	6	41.1	1,740	1.10	46.7	10.6	2.7	15.2
	8	51.7	2,190	1.39	58.7	18.8	5.9	8.9
A-12	2	14.7	623	.29	12.2	.9	.3	56.3
	4	25.4	1,080	.50	21.1	3 3	.8	30.3
	6	35.4	1,500	.69	29.4	7.5	2.1	17.3
	8	44.9	1.900	.88	37.2	13.3	4.3	10.7
A-13	2	15.8	670	.36	15.3	.9	.2	68.0
	4	27.4	1,160	.62	26.4	3.4	.8	35.2
	6	38 5	1,630	.88	37.1	7.5	1.9	19.9
	8	49.2	2.090	1.12	47.6	12.9	4.0	12.3
A-14	2	19.3	819	.42	17.7	1.5	.4	46.8
	4	33.8	1,430	.73	30.9	5.9	1.5	22.6
	6	45.7	1,940	.99	41.9	13.4	3.9	11.7
	8	56.2	2,380	1.21	51.4	23 8	8.3	6.7
A-15	2	15.6	662	.44	18.8	1.9	.4	40.0
	4	29.2	1,240	.83	35.1	7.2	1.6	18.2
	6	42.2	1,790	1.20	50.7	16.5	4.7	9.0
	8	54.7	2,320	1.55	65.7	29.7	10.5	5.2
A-16	2	13.4	568	.39	16.4	.7	.2	63.0
	4	22.9	971	.66	28.0	2.9	.7	32.5
	6	31.7	1,340	.92	38.7	6.6	1.8	18.0
	8	39.8	1,690	1.15	48.8	11.8	3.7	11.0
A-17	2	15.7	666	.33	14.1	.9	.3	54.0
	4	28.1	1,190	.60	25.3	3.7	.9	29.5
	6	39 8	1,690	.85	35.9	8.3	2.3	17.2
	8	51.2	2,170	1.09	46.1	14.7	4.9	10.7
A-18	2	9.4	399	.34	14.5	.6	.2	56.7
	4	15 2	645	.55	23.4	2 4	.6	27.7
	6	19 3	819	.70	29.7	5.3	1.4	14.2
	8	22 5	954	.82	34.6	9.5	2.9	8.2
A-19	2	15 6	662	.38	16.4	.8	.3	60.1
	4	27.7	1,170	.68	29.0	3.4	.8	32.4
	6	39 2	1,660	.97	41.2	7.5	2.1	18.7
	8	50.7	2,150	1.26	53.3	13.4	4.4	11.7
A-20	2	23.6	1,000	.35	15.0	1.6	.5	46.0
	4	42.6	1,810	.64	27.1	5.9	1.7	24.9
	6	60.2	2,550	.90	38.2	13.2	4.2	14.4
	8	76.7	3,250	1.15	48.7	23.6	8.7	8.9

TABLE II.—*Radiator performance in terms of mass flow of air*—Continued.

Radiator.	Air flow.	Energy dissipated per square foot—				Head resistance.	H. P. absorbed.	Figure of merit.
		Front.		Surface.				
		H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
A-21	2	12.1	513	0.38	16.3	1.1	0.2	49.4
	4	21.2	899	.67	28.5	4.3	.9	23.2
	6	30.3	1,280	.96	40.6	9.5	2.5	12.3
	8	39.3	1,670	1.25	53.0	17.0	5.5	7.3
A-22	2	15.6	662	.37	15.6	1.0	.3	53.2
	4	28.2	1,200	.66	28.2	4.3	1.0	27.2
	6	39.6	1,680	.93	39.5	9.6	2.7	14.7
	8	60.3	2,130	1.18	50.2	17.3	5.7	8.9
A-23	2	18.0	763	.33	14.0	1.1	.4	50.3
	4	33.1	1,400	.61	25.7	4.3	1.2	28.7
	6	47.0	1,990	.86	36.5	9.5	2.8	16.8
	8	60.4	2,560	1.11	47.0	16.5	5.7	10.6
B-1	2	9.0	382	.42	17.7	.6	.1	77.0
	4	15.0	636	.69	29.5	2.1	.4	37.0
	6	19.8	840	.92	38.9	4.7	1.1	18.7
	8	23.8	1,010	1.10	46.7	8.4	2.3	10.5
	10	27.5	1,170	1.27	54.1	13.1	4.2	6.4
B-2	2	12.5	530	.35	14.7	.6	.2	72.0
	4	19.3	819	.53	22.7	2.5	.5	35.2
	6	24.6	1,040	.68	28.8	5.7	1.4	17.7
	8	29.1	1,230	.81	34.1	10.0	2.9	10.0
	10	33.3	1,410	.92	39.1	15.7	5.3	6.2
B-3	2	10.1	428	.38	16.0	.6	.2	62.0
	4	17.0	721	.63	26.9	2.4	.5	31.5
	6	22.7	963	.85	35.9	5.5	1.3	16.7
	8	27.7	1,170	1.03	43.7	9.9	2.8	9.8
	10	32.5	1,380	1.21	51.5	15.5	5.2	6.1
B-4	2	18.8	797	.51	21.4	1.2	.3	67.5
	4	29.1	1,230	.78	33.1	4.9	1.1	27.6
	6	37.5	1,590	1.01	42.7	10.9	2.8	13.2
	8	45.2	1,920	1.22	51.6	19.4	6.2	7.2
B-5	2	10.1	428	.42	18.0	.7	.1	81.0
	4	15.0	636	.63	26.7	3.0	.5	29.2
	6	19.1	814	.80	34.2	6.7	1.5	13.2
	8	22.8	867	.96	40.6	11.9	3.3	7.1
B-6	2	14.7	623	.39	16.4	.9	.2	79.0
	4	21.8	925	.58	24.4	3.5	.7	31.4
	6	27.6	1,170	.73	30.9	7.9	1.9	14.7
	8	33.0	1,400	.87	36.9	14.0	4.1	8.2
	10	38.3	1,620	1.01	42.7	21.9	7.7	5.1
B-7	2	17.3	734	.38	16.0	1.1	.2	71.0
	4	26.5	1,120	.58	24.4	4.6	1.0	28.0
	6	33.8	1,430	.74	31.2	10.2	2.6	13.2
	8	40.1	1,700	.88	37.1	18.1	5.7	7.0
B-8	2	19.5	827	.35	14.7	1.6	.4	52.9
	4	29.9	1,270	.53	22.6	6.2	1.5	20.1
	6	38.4	1,630	.68	29.0	13.8	3.9	9.9
	8	46.2	1,960	.82	34.9	24.6	8.5	5.3
B-9	2	13.7	582	.38	16.1	1.4	.3	48.3
	4	24.6	1,040	.68	28.7	5.5	1.2	20.9
	6	34.7	1,470	.96	40.6	12.4	3.3	10.7
	8	43.3	1,840	1.20	50.8	21.8	7.1	6.2
B-10	2	11.8	500	.46	19.6	1.1	.2	55.5
	4	20.8	882	.82	34.6	4.3	.9	24.7
	6	29.5	1,250	1.16	49.0	9.5	2.4	12.7
	8	37.7	1,600	1.48	62.7	16.8	5.1	7.4
B-11	2	14.0	594	.46	19.5	1.5	.3	50.1
	4	24.4	1,040	.80	34.2	5.8	1.3	20.4
	6	33.7	1,430	1.11	47.0	13.0	3.4	10.0
	8	42.5	1,800	1.40	59.2	23.3	7.6	5.7
B-12	2	15.0	636	.44	18.7	1.2	.3	58.0
	4	26.1	1,110	.77	32.6	4.8	1.0	26.1
	6	36.0	1,530	1.06	45.0	10.7	2.7	13.2
	8	45.5	1,930	1.34	56.8	19.0	6.0	7.6
B-13	2	15.5	657	.37	15.8	1.5	.3	44.8
	4	28.3	1,200	.68	28.9	5.9	1.4	20.9
	6	40.6	1,720	.98	41.3	13.5	3.7	11.0
	8	52.0	2,200	1.25	52.9	23.9	8.0	6.5
C-1	2	12.5	530	.39	16.5	2.5	.5	25.2
	4	24.2	1,030	.75	32.1	9.7	2.3	10.3
	6	35.7	1,510	1.11	47.0	22.3	6.9	5.1
C-2	2	15.8	670	.33	13.9	1.1	.4	37.6
	4	28.3	1,200	.59	24.8	4.4	1.3	22.3
	6	39.6	1,680	.82	34.8	9.7	3.0	13.2
	8	50.4	2,140	1.04	44.3	17.2	6.0	8.4
C-2a	2	19.7	835	.26	10.9	2.0	.6	30.6
	4	29.9	1,270	.39	16.8	7.4	2.2	13.8
	6	38.3	1,620	.50	21.1	16.3	5.6	6.9
	8	45.8	1,940	.60	25.3	28.5	11.5	3.9

TABLE II.—*Radiator performance in terms of mass flow of air*—Continued.

Radiator.	Air flow.	Energy dissipated per square foot—				Head resistance.	H. P. absorbed.	Figure of merit.
		Front.		Surface.				
		H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
C–2b (vanes in front)	2	24.3	1,030	0.43	18.2	1.8	0.5	46.5
	4	37.0	1,570	.65	27.7	7.1	2.0	19.1
	6	47.8	2,030	.84	35.8	16.3	5.2	9.3
	8	57.5	2,440	1.01	43.0	28.5	11.1	4.9
C–2b (vanes in rear)	2	21.8	925	.38	16.3	1.6	.3	44.2
	4	33.5	1,420	.59	23.0	6.5	1.9	19.1
	6	42.7	1,810	.75	31.9	14.7	4.7	9.3
	8	50.7	2,150	.89	37.9	26.0	9.8	4.9
C–4	2	12.9	547	.40	17.1	1.0	.2	57.2
	4	22.6	959	.71	30.0	3.9	.9	27.4
	6	32.2	1,370	1.01	42.6	8.6	2.2	14.6
	8	41.4	1,760	1.30	55.0	15.3	4.7	8.9
C–5	2	15.6	662	.45	19.0	1.7	.5	30.7
	4	29.0	1,230	.83	35.0	6.8	1.9	15.8
	6	41.0	1,740	1.17	50.0	15.2	4.8	8.6
	8	52.2	2,210	1.49	63.0	27.1	10.2	5.2
C–6	2	15.6	662	.51	21.8	.9	.2	71.5
	4	24.8	1,050	.82	34.5	3.7	.8	30.6
	6	32.6	1,380	1.07	45.4	8.3	2.2	15.4
	8	39.6	1,680	1.30	55.2	15.1	4.6	8.7
C–7	2	14.6	619	.45	19.1	1.1	.3	55.2
	4	25.2	1,070	.78	32.9	4.4	1.0	25.8
	6	34.7	1,470	1.07	45.3	9.9	2.6	13.3
	8	43.5	1,840	1.34	56.6	17.9	5.7	7.8
D–1	2	11.5	488	.49	20.6	.8	.2	60.8
	4	21.5	912	.91	38.5	3.3	.7	30.8
	6	28.6	1,210	1.21	51.0	7.3	1.9	15.5
	8	34.4	1,460	1.45	61.6	12.9	3.9	8.8
D–2	2	26.0	1,100	.31	13.1	2.9	1.0	28.0
	4	41.5	1,760	.49	20.9	11.3	3.6	11.7
	6	54.7	2,320	.65	27.6	25.2	9.5	5.7
D–3	2	15.3	649	.47	19.9	2.8	.5	27.4
	4	27.9	1,140	.86	35.0	10.3	2.4	11.3
	6	40.2	1,700	1.23	52.1	22.9	7.0	5.7
D–4	2	14.8	628	.35	14.9	1.1	.2	62.5
	4	24.5	1,040	.58	24.7	4.1	.9	28.2
	6	32.9	1,400	.78	33.3	9.1	2.3	14.3
	8	40.6	1,720	.97	40.9	16.1	4.9	8.2
E–4	2	18.4	780	.62	26.4	1.7	.5	37.4
	3	26.0	1,100	.88	37.3	4.4	1.1	23.5
	4	32.7	1,390	1.11	47.1	7.9	2.1	15.7
E–6	2	27.8	1,180	.35	15.0	1.4	.5	59.8
	4	48.8	2,070	.62	26.4	5.6	1.7	31.2
	6	67.8	2,870	.86	36.6	12.5	3.9	17.3
	8	85.0	3,600	1.08	45.8	22.4	8.2	10.6
E–7	2	15.8	670	.30	12.8	.7	.3	63.0
	4	29.7	1,260	.57	24.1	2.7	.8	39.0
	6	42.6	1,810	.81	34.6	6.0	1.8	23.9
	8	55.1	2,340	1.05	44.7	10.7	3.6	15.5
	10	67.0	2,840	1.28	54.3	16.7	6.4	10.6
E–8	2	13.4	568	.34	14.5	.5	.1	75.0
	4	23.2	984	.59	25.1	1.7	.5	46.5
	6	32.0	1,360	.82	34.7	3.7	1.2	28.8
	8	40.1	1,700	1.02	43.4	6.7	2.2	18.7
	10	48.0	2,030	1.22	51.9	10.4	3.9	12.8
E–9	2	18.3	775	.27	11.4	1.3	.7	24.0
	4	38.4	1,630	.53	22.5	5.5	2.1	17.8
	6	54.7	2,320	.79	33.5	11.7	4.4	12.3
	8	72.9	3,090	1.06	44.9	20.6	8.5	8.6
F–5	2	14.7	623	.43	18.1	3.0	.5	36.0
	4	23.0	975	.67	28.3	11.7	2.3	9.9
	6	29.4	1,250	.85	36.1	26.2	7.3	4.1
G–1	2	12.3	522	.45	19.2	3.8	.6	21.2
	4	19.0	806	.70	29.6	13.9	3.2	6.2
	6	23.9	1,010	.88	37.1	30.6	9.5	2.5
G–2	2	14.7	623	.66	27.8	1.6	.3	67.5
	4	23.0	977	1.03	43.6	6.3	1.2	20.6
	6	30.0	1,270	1.34	56.7	14.1	3.5	8.9
	8	36.6	1,550	1.63	69.2	25.3	7.9	4.7
G–3	2	24.3	1,030	.54	23.0	2.7	.5	54.0
	4	41.5	1,760	.93	39.3	9.8	2.1	19.8
	6	56.4	2,390	1.26	53.5	21.6	6.2	9.2
	8	70.7	3,000	1.58	67.1	38.0	13.9	5.1
G–4	2	20.8	882	.40	16.9	3.6	.8	27.6
	4	33.1	1,400	.63	26.8	10.8	2.7	12.3
	6	44.7	1,900	.86	36.4	22.1	6.9	6.5

TABLE III.—*Radiator performance in terms of free air speed (for unobstructed positions only).*

Speed is in miles per hour.
Grade A represents very good performance; grade E, very poor.
All units the same as in Table II.

Radiator.	Speed.	Air flow.	Energy dissipated per square foot—				Head resistance.	H. P. absorbed.	Figure of merit.
			Front.		Surface.				
			H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
A-1	30	2.31	21.9	929	0.56	23.6	1.56	0.36	61.0
	60	4.62	36.6	1,550	.93	39.5	6.23	1.46	25.0
	90	6.93	49.2	2,080	1.25	53.0	14.01	4.06	12.1
	120	9.25	60.6	2,570	1.54	65.3	24.9	8.90	6.8
Grade			B				D	D	C
A-2	30	2.23	22.6	958	.44	18.5	1.63	.45	50.7
	60	4.47	40.3	1,710	.78	32.9	6.52	1.68	24.1
	90	6.70	56.1	2,380	1.08	45.8	14.66	4.47	12.5
	120	8.93	71.4	3,030	1.38	58.3	26.1	9.65	7.4
Grade			B				D	D	C
A-3	30	2.74	15.3	649	.50	21.4	1.00	.24	62.7
	60	5.51	25.0	1,060	.83	35.0	4.00	.97	25.9
	90	8.26	33.2	1,410	1.10	46.4	9.00	2.65	12.5
	120	11.01	40.3	1,710	1.33	56.4	16.0	5.78	7.0
Grade			D				A	B	C
A-4	30	2.63	16.0	679	.56	23.7	1.33	.31	51.7
	60	5.25	27.4	1,160	.96	40.6	5.33	1.26	21.7
	90	7.88	37.4	1,580	1.31	55.4	12.00	3.49	10.7
	120	10.50	46.0	1,950	1.61	68.2	21.3	7.64	6.0
Grade			D				C	C	C
A-5	30	2.40	18.5	784	.51	21.4	1.45	.31	59.0
	60	4.80	31.6	1,340	.86	36.6	5.80	1.32	23.9
	90	7.20	43.5	1,840	1.19	50.4	13.03	3.72	11.7
	120	9.60	54.8	2,320	1.50	63.4	23.2	8.22	6.7
Grade			C				C	C	C
A-6	30	2.34	20.2	857	.41	17.6	1.54	.38	53.3
	60	4.68	35.2	1,490	.72	30.4	6.16	1.50	23.5
	90	7.02	48.3	2,050	.98	41.7	13.95	4.06	11.9
	120	9.36	60.9	2,580	1.24	52.6	24.6	8.90	6.8
Grade			C				C	D	C
A-7	30	2.20	27.2	1,150	.43	18.4	1.72	.50	54.6
	60	4.40	45.9	1,950	.73	31.1	6.70	1.79	25.7
	90	6.60	61.7	2,620	.99	41.8	14.90	4.66	13.2
	120	8.80	76.5	3,240	1.22	51.8	26.3	9.87	7.8
Grade			A				D	D	B
A-8	30	2.41	15.3	649	.50	21.4	1.54	.28	53.9
	60	4.81	26.4	1,120	.87	36.9	5.87	1.26	20.9
	90	7.22	36.6	1,550	1.21	51.2	12.80	3.56	10.4
	120	9.62	46.3	1,960	1.53	64.8	22.3	7.78	6.0
Grade			D				C	C	C
A-9	30	2.31	19.0	806	.51	21.6	1.56	.32	59.4
	60	4.62	33.3	1,410	.89	37.7	6.23	1.39	24.0
	90	6.92	45.9	1,950	1.23	52.2	14.00	3.95	11.6
	120	9.22	58.0	2,460	1.55	65.9	24.9	8.75	6.6
Grade			C				D	C	C
A-12	30	2.51	17.4	738	.34	14.4	1.31	.36	47.7
	60	5.02	30.6	1,300	.60	25.4	5.25	1.36	22.5
	90	7.53	42.7	1,810	.84	35.4	11.82	3.63	11.8
	120	10.04	54.5	2,310	1.07	45.2	21.0	7.77	7.0
Grade			C				C	C	C
A-13	30	2.50	18.8	797	.43	18.1	1.40	.33	57.5
	60	5.00	33.0	1,400	.75	31.9	5.23	1.27	26.1
	90	7.50	46.5	1,970	1.06	44.9	11.37	3.38	13.8
	120	10.00	59.9	2,540	1.36	57.9	19.9	7.24	8.3
Grade			C				C	C	B
A-14	30	2.13	20.3	861	.44	18.6	1.68	.46	44.5
	60	4.26	35.4	1,500	.76	32.4	6.74	1.72	20.5
	90	6.39	47.8	2,020	1.03	43.7	15.15	4.60	10.4
	120	8.52	58.7	2,490	1.27	53.8	26.9	9.91	5.9
Grade			C				D	D	C
A-15	30	1.98	15.3	649	.43	18.4	1.93	.38	40.5
	60	3.98	29.0	1,230	.82	34.8	7.03	1.57	18.5
	90	5.94	41.7	1,770	1.18	50.0	16.20	4.5 6	9.1
	120	7.92	54.0	2,290	1.53	64.9	29.0	10.2	5.3
Grade			C				D	D	D
A-16	30	2.55	16.2	687	.47	19.8	1.20	.31	52.2
	60	5.11	28.0	1,190	.81	34.3	4.83	1.20	23.3
	90	7.66	38.5	1,630	1.11	47.2	10.85	3.25	11.9
	120	10.21	48.4	2,050	1.40	59.3	19.3	7.05	6.9
Grade			D				B	C	C

TABLE III.—*Radiator performance in terms of free air speed (for unobstructed positions only)*—Continued.

Radiator.	Speed.	Air flow.	Energy dissipated per square foot—				Head resistance.	H. P. absorbed.	Figure of merit.
			Front.		Surface.				
			H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
A-17	30	2.42	18.4	780	0.39	16.6	1.34	0.39	47.7
	60	4.83	33.0	1,400	.70	29.7	5.36	1.41	23.3
	90	7.25	47.0	1,990	1.00	42.3	12.06	3.73	12.6
	120	9.66	60.4	2,560	1.28	54.4	21.5	7.99	7.6
Grade			C				C	C	C
A-18	30	2.64	11.5	488	.42	17.7	1.02	.26	44.9
	60	5.28	17.9	759	.65	27.5	4.11	1.01	17.8
	90	7.92	22.4	950	.81	34.4	9.24	2.74	8.2
	120	10.56	26.0	1,100	.94	40.0	16.41	5.95	4.4
Grade			E				B	B	D
A-19	30	2.45	18.3	772	.45	19.1	1.26	.35	52.3
	60	4.91	32.8	1,390	.81	34.5	5.05	1.31	25.1
	90	7.36	46.9	1,990	1.16	49.3	11.35	3.47	13.5
	120	9.82	61.0	2,590	1.51	64.3	20.2	7.46	8.2
Grade			C				C	C	B
A-20	30	2.10	24.7	1,050	.37	15.7	1.62	.55	44.9
	60	4.21	44.5	1,890	.67	28.2	6.49	1.88	23.7
	90	6.31	62.9	2,670	.94	39.9	14.60	4.76	13.2
	120	8.41	80.5	3,410	1.20	51.0	25.9	9.97	8.1
Grade			A				D	D	B
A-21	30	2.29	13.4	568	.43	18.0	1.39	.30	44.5
	60	4.58	23.8	1,010	.76	32.0	5.55	1.27	18.7
	90	6.88	34.2	1,450	1.09	46.0	12.49	3.57	9.6
	120	9.17	44.5	1,890	1.41	59.8	22.2	7.87	5.7
Grade			D				C	C	D
A-22	30	2.28	17.5	742	.41	17.5	1.40	.36	48.4
	60	4.55	31.3	1,330	.74	31.3	5.58	1.39	22.5
	90	6.83	44.0	1,860	1.04	43.9	12.55	3.76	11.7
	120	9.10	56.0	2,370	1.32	55.9	22.3	8.13	6.9
Grade			C				C	C	C
A-23	30	2.29	20.3	861	.37	15.8	1.40	.44	46.6
	60	4.58	37.2	1,580	.68	28.9	5.61	1.54	24.1
	90	6.87	52.9	2,240	.97	41.2	12.10	3.88	13.6
	120	9.16	68.0	2,880	1.25	53.0	21.3	8.11	8.4
Grade			B				C	C	B
B-1	30	2.76	11.5	488	.53	22.6	1.00	.20	59.0
	60	5.52	18.7	793	.87	36.7	4.00	.87	21.5
	90	8.29	24.4	1,040	1.13	47.9	9.00	2.51	9.7
	120	11.05	29.5	1,250	1.37	58.0	16.0	5.58	5.3
Grade			E				B	B	D
B-2	30	2.67	15.0	636	.42	17.6	1.12	.26	58.1
	60	5.35	22.9	971	.63	26.9	4.47	1.05	21.8
	90	8.02	29.2	1,240	.81	34.3	10.05	2.92	10.0
	120	10.70	34.7	1,470	.96	40.8	17.9	6.40	5.4
Grade			E				B	B	D
B-3	30	2.68	12.7	538	.47	20.1	1.11	.26	49.6
	60	5.36	20.9	886	.78	33.1	4.43	1.04	20.1
	90	8.04	27.9	1,180	1.04	44.1	9.97	2.89	9.7
	120	10.72	34.2	1,450	1.28	54.1	17.7	6.34	5.4
Grade			E				B	B	D
B-4	30	2.28	20.4	866	.55	23.3	1.57	.34	64.2
	60	4.56	31.6	1,340	.85	36.0	6.30	1.44	22.0
	90	6.85	40.9	1,730	1.10	46.6	14.20	4.05	10.1
	120	9.13	49.3	2,090	1.33	56.2	25.2	8.92	5.5
Grade			C				D	C	C
B-5	30	2.58	11.6	492	.49	20.7	1.23	.19	59.6
	60	5.16	17.4	738	.73	31.0	4.94	.98	17.7
	90	7.74	22.4	950	.94	39.9	11.10	2.95	7.6
	120	10.32	26.7	1,130	1.12	47.5	19.7	6.70	4.0
Grade			E				C	B	D
B-6	30	2.48	16.6	704	.44	18.6	1.35	.26	63.1
	60	4.98	24.7	1,050	.65	27.6	5.40	1.17	21.1
	90	7.46	31.5	1,340	.83	35.2	12.15	3.38	9.3
	120	9.95	38.2	1,620	1.01	42.7	21.6	7.54	5.1
Grade			D				C	C	D
B-7	30	2.33	19.0	806	.42	17.6	1.53	.31	60.5
	60	4.67	29.1	1,230	.64	27.0	6.12	1.36	21.4
	90	7.00	37.1	1,570	.81	34.4	13.77	3.88	9.6
	120	9.32	44.0	1,860	.96	40.7	24.5	8.61	5.1
Grade			D				C	C	D
B-8	30	2.12	20.2	857	.36	15.3	1.72	.41	49.8
	60	4.24	31.0	1,310	.55	23.5	6.88	1.64	18.9
	90	6.36	39.8	1,690	.71	30.1	15.48	4.52	8.8
	120	8.48	47.9	2,030	.85	36.2	27.5	9.89	4.8
Grade			D				D	D	D

TABLE III.—*Radiator performance in terms of free air speed (for unobstructed positions only)*—Continued.

Radiator.	Speed.	Air flow.	Energy dissipated per square foot— Front. H. P.	Front. B. t. u. / Min.	Surface. H. P.	Surface. B. t. u. / Min.	Head resistance.	H. P. absorbed.	Figure of merit.
B-9	30	2.21	14.9	632	0.41	17.5	1.66	0.35	43.1
	60	4.42	26.7	1,130	.74	31.2	6.67	1.49	17.9
	90	6.64	37.6	1,600	1.04	43.2	15.00	4.24	8.9
	120	8.85	46.7	1,980	1.29	54.7	26.6	9.37	5.0
Grade			C				D	D	D
B-10	30	2.38	13.5	572	.53	22.4	1.48	.29	46.9
	60	4.75	24.2	1,03	.95	40.2	5.90	1.28	18.7
	90	7.13	34.1	1,450	1.34	56.7	13.29	3.70	9.2
	120	9.50	43.6	1,850	1.71	72.5	23.6	8.23	5.3
Grade			D				C	C	D
B-11	30	2.18	14.9	632	.49	20.8	1.71	.33	45.7
	60	4.35	25.9	1,100	.85	36.1	6.85	1.47	17.6
	90	6.53	35.9	1,520	1.18	49.8	15.40	4.26	8.4
	120	8.70	45.3	1,920	1.49	63.2	27.4	9.53	4.8
Grade			D				D	D	D
B-12	30	2.30	16.8	712	.49	20.9	1.57	.33	51.6
	60	4.61	29.3	1,240	.86	36.6	6.27	1.49	20.9
	90	6.91	40.4	1,710	1.19	50.4	14.10	3.99	10.1
	120	9.21	51.0	2,160	1.50	63.6	25.1	8.85	5.8
Grade			C				D	C	C
B-13	30	2.16	16.5	700	.40	16.8	1.73	.39	41.9
	60	4.31	30.3	1,280	.73	30.9	6.91	1.62	18.7
	90	6.46	43.3	1,840	1.04	44.2	15.55	4.50	9.6
	120	8.61	55.3	2,340	1.33	56.4	27.6	9.85	5.6
Grade			C				D	D	D
C-1	30	1.74	11.0	466	.34	14.5	1.86	.39	28.4
	60	3.49	21.2	899	.66	28.0	7.45	1.67	12.7
	90	5.23	31.2	1,320	.97	41.2	16.78	4.74	6.6
	120	6.97	41.4	1,760	1.29	54.7	29.8	10.5	3.8
Grade			C				D	D	E
C-2	30	2.37	18.3	776	.38	16.1	1.63	.54	34.2
	60	4.74	32.5	1,380	.67	28.5	6.13	1.79	18.2
	90	7.11	45.8	1,940	.95	40.0	13.60	4.47	10.3
	120	9.47	58.2	2,470	1.20	51.1	24.0	9.30	6.3
Grade			C				C	D	C
C-2a	30	1.89	18.9	802	.25	10.5	1.82	.59	32.0
	60	3.79	29.0	1,230	.38	16.1	6.66	1.95	14.8
	90	5.68	37.0	1,570	.48	20.5	14.65	4.85	7.6
	120	7.57	44.2	1,870	.58	24.5	25.7	10.0	4.4
Grade			D				D	D	D
C-2b (vanes in front)	30	1.91	23.5	997	.41	17.6	1.80	.50	46.6
	60	3.81	35.9	1,520	.63	26.8	6.61	1.78	20.2
	90	5.72	46.4	1,970	.82	34.7	14.60	4.58	10.1
	120	7.62	55.8	2,370	.98	41.7	25.6	9.6	5.8
Grade			C				D	D	C
C-2b (vanes in rear)	30	1.99	21.7	920	.38	16.2	1.76	.50	43.4
	60	3.97	33.3	1,410	.59	24.9	6.55	1.77	18.8
	90	5.96	42.5	1,800	.75	31.8	14.45	4.54	9.4
	120	7.94	50.5	2,140	.89	37.7	25.4	9.56	5.3
Grade			C				D	D	D
C-4	30	2.40	14.8	628	.46	19.6	1.37	.30	48.7
	60	4.80	26.4	1,120	.83	35.0	5.47	1.26	20.9
	90	7.20	37.8	1,600	1.18	50.1	12.30	3.53	10.7
	120	9.60	48.5	2,060	1.52	64.2	21.9	7.79	6.2
Grade			D				C	C	C
C-5	30	2.01	15.7	666	.45	19.	1.70	.51	30.6
	60	4.01	29.1	1,230	.83	35.	6.81	1.84	15.8
	90	6.01	41.0	1,740	1.17	50.	15.31	4.81	8.5
	120	8.02	52.3	2,220	1.49	63.	27.2	10.2	5.1
Grade			C				D	D	D
C-6	30	2.44	17.7	751	.58	24.7	1.39	.30	59.0
	60	4.88	28.3	1,200	.93	39.5	5.58	1.27	22.3
	90	7.33	37.3	1,580	1.23	52.0	12.56	3.58	10.4
	120	9.77	45.2	1,920	1.48	63.0	22.3	7.90	5.7
Grade			D				C	C	C
C-7	30	2.35	16.5	700	.51	21.5	1.52	.34	48.7
	60	4.70	28.5	1,210	.88	37.2	6.08	1.40	20.3
	90	7.05	39.3	1,670	1.21	51.3	13.70	3.94	10.0
	120	9.39	49.4	2,090	1.52	64.5	24.3	8.64	5.7
Grade			D				C	C	C
D-1	30	2.41	13.8	585	.58	24.7	1.25	.26	53.5
	60	4.82	24.7	1,050	1.04	44.2	4.75	1.08	23.0
	90	7.22	32.3	1,370	1.32	55.7	10.48	2.99	10.8
	120	9.63	38.7	1,640	1.63	69.2	18.4	6.53	5.9
Grade			D				B	B	C

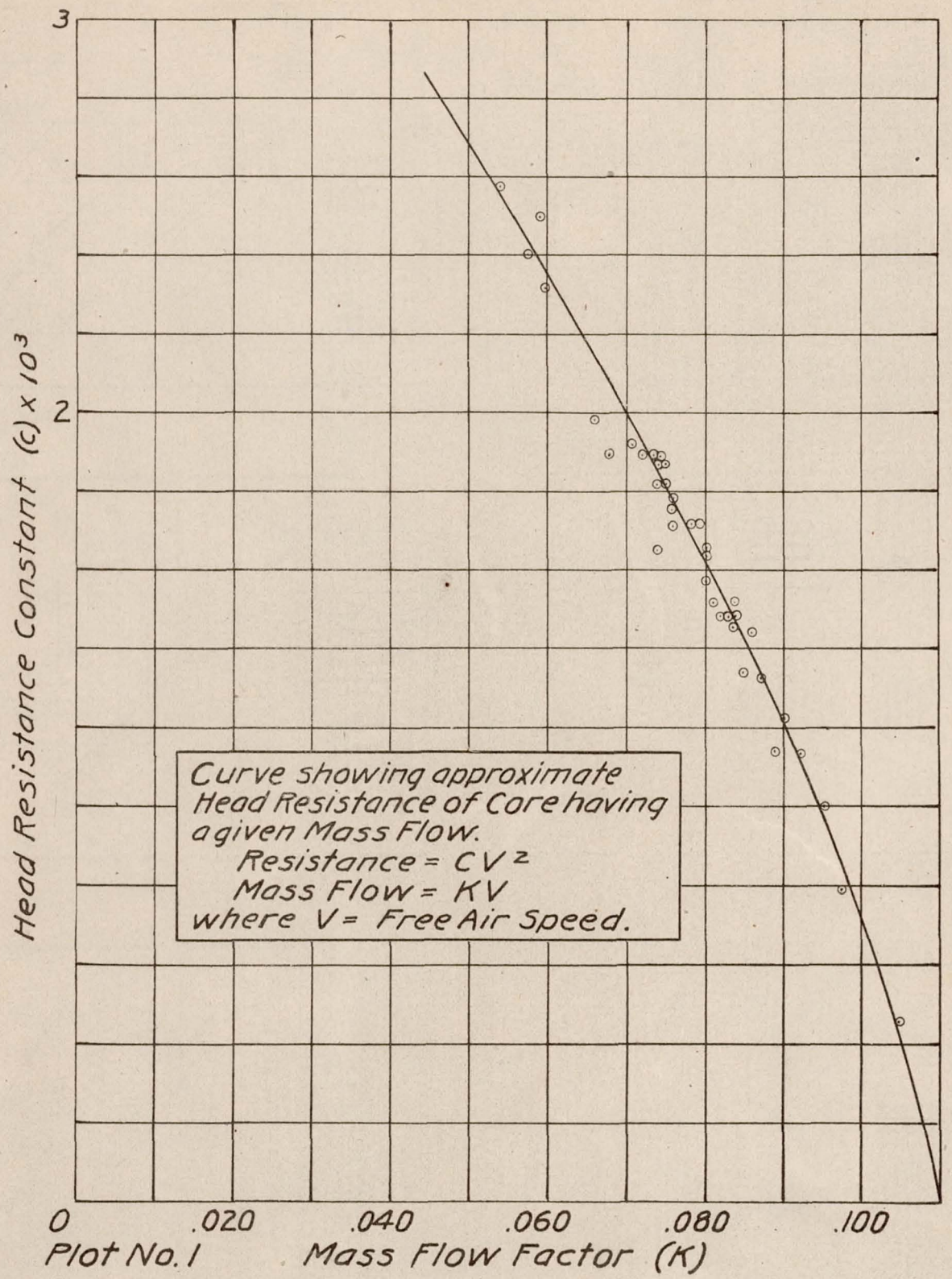
TABLE III.—*Radiator performance in terms of free air speed (for unobstructed positions only)*—Continued.

Radiator.	Speed.	Air flow.	Energy dissipated per square foot.				Head resistance.	H. P. absorbed.	Figure of merit.
			Front.		Surface.				
			H. P.	B. t. u. / Min.	H. P.	B. t. u. / Min.			
D-2	30	1.58	22.7	963	0.27	11.4	1.83	0.65	34.8
	60	3.16	35.1	1,490	.42	17.7	7.14	2.15	16.3
	90	4.75	46.7	1,980	.56	23.6	15.9	5.33	8.8
	120	6.33	56.5	2,400	.67	28.5	28.0	11.0	5.1
Grade			C				D	E	D
D-3	30	1.80	14.1	598	.43	18.3	2.27	.46	30.4
	60	3.59	25.3	1,070	.78	33.0	8.30	1.89	13.4
	90	5.38	36.3	1,540	1.11	47.2	18.5	5.28	6.9
	120	7.18	47.2	2,000	1.45	61.4	32.4	11.5	4.1
Grade			D				E	E	E
D-4	30	2.41	17.0	721	.40	17.2	1.60	.32	52.8
	60	4.82	28.0	1,190	.67	28.3	5.90	1.33	21.0
	90	7.23	37.7	1,600	.90	38.1	13.1	3.73	10.1
	120	9.63	46.6	1,980	1.11	47.0	23.0	8.13	5.7
Grade			D				C	C	C
E-4 (properties are irregular)	30	1.93	17.7	751	.60	25.4	1.62	.46	38.1
	60	3.70	30.8	1,310	1.04	44.3	6.73	1.75	17.6
	90						16.0	4.61	
Grade			C				D	D	C
E-6	30	2.12	29.3	1.240	.37	15.8	1.57	.51	57.2
	60	4.24	51.1	2,170	.65	27.6	6.27	1.78	28.8
	90	6.36	71.3	3,020	.91	38.6	14.10	4.54	15.7
	120	8.48	90.5	3,840	1.15	48.9	25.1	9.59	9.5
Grade			A				D	D	B
E-7	30	2.51	19.6	831	.38	15.9	1.04	.35	56.7
	60	5.01	36.3	1,540	.69	29.4	4.17	1.19	30.4
	90	7.52	52.0	2,200	.99	42.2	9.38	3.03	17.2
	120	10.02	67.2	2,850	1.28	54.5	16.7	6.39	10.5
Grade			B				B	C	A
E-8	30	2.74	17.2	729	.44	18.6	.78	.27	63.3
	60	5.48	29.8	1,260	.76	32.2	3.12	.92	32.4
	90	8.23	41.0	1,740	1.05	44.4	7.03	2.31	17.8
	120	10.97	51.7	2,190	1.32	55.9	12.5	4.84	10.7
Grade			C				A	A	A
E-9	30	2.24	20.4	865	.30	12.7	1.67	.86	23.8
	60	4.48	40.9	1,730	.59	25.0	6.61	2.50	16.3
	90	6.72	61.2	2,600	.89	37.7	14.6	5.67	10.8
	120	9.96	81.5	3,460	1.18	50.0	25.9	11.2	7.3
Grade			A				D	E	C
F-5	30	1.82	13.8	585	.40	17.0	2.52	.33	41.3
	60	3.64	21.7	920	.63	26.7	9.65	1.81	12.0
	90	5.46	27.8	1,180	.81	34.2	21.6	5.57	5.0
	120	7.28	33.0	1,400	.96	40.6	38.3	12.8	2.6
Grade			E				E	E	E
G-1	30	1.62	10.7	454	.39	16.7	2.35	.34	31.6
	60	3.24	16.7	708	.61	26.0	9.25	1.78	9.4
	90	4.85	21.3	903	.78	33.2	20.3	5.32	4.0
	120	6.47	24.8	1,050	.91	38.6	35.	11.8	2.1
Grade			E				E	E	E
G-2	30	2.16	15.3	649	.68	29.0	1.85	.25	60.7
	60	4.33	24.2	1,030	1.08	45.8	7.39	1.39	17.4
	90	6.49	31.6	1,340	1.41	59.8	16.6	4.30	7.4
	120	8.65	38.7	1,640	1.73	73.3	29.5	9.86	3.9
Grade			D				D	D	D
G-3	30	1.88	23.1	980	.52	21.9	2.40	.40	58.0
	60	3.75	39.5	1,680	.88	37.5	8.65	1.80	22.0
	90	5.62	53.6	2,270	1.20	50.8	19.1	5.21	10.3
	120	7.50	67.0	2,840	1.50	63.5	33.4	11.5	5.8
Grade			B				E	E	C
G-4	30	1.46	17.2	729	.33	13.9	2.43	.49	35.1
	60	3.39	29.5	1,250	.56	23.9	8.25	1.91	15.5
	90	5.30	40.7	1,720	.78	32.9	17.70	5.13	7.9
	120	7.20	51.3	2.170	.98	41.5	31.0	11.1	4.6
Grade			C				D	E	D

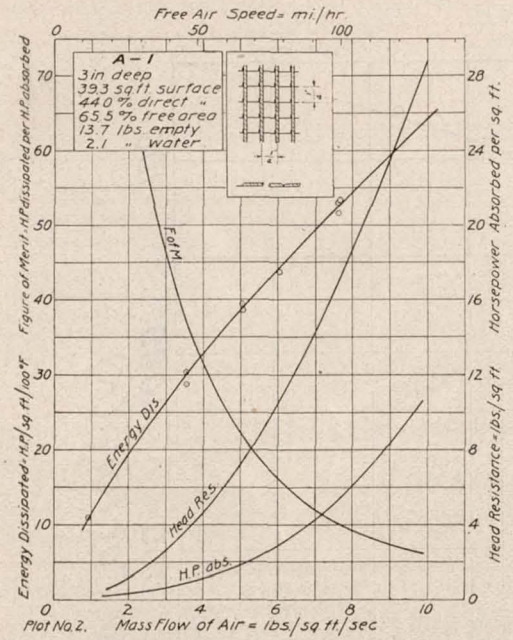
TABLE IV.—*Constants in the equations* $R=cV^2$; $M=kV$; *and* $Q=GM^n$.

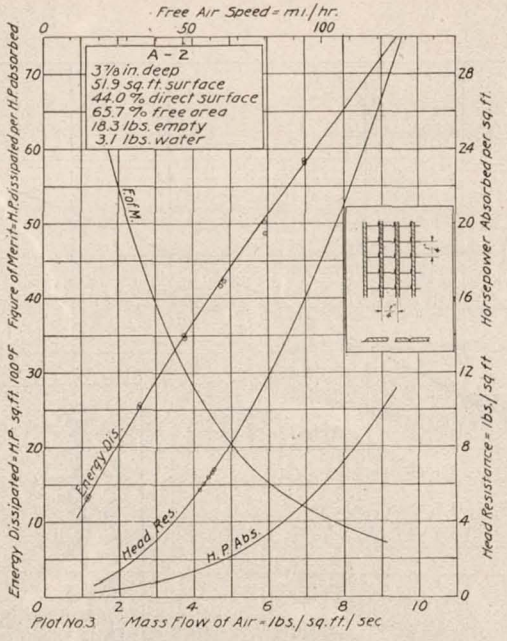
R=head resistance in lb./sq. ft.
V=free air speed in mi./hr.
M=mass flow of air in pound per second per square foot.
Q=energy dissipated in horsepower per square foot per 100° F.
m="mass flow constant," which is the ratio of the mass of air passing through 1 square foot of radiator to the mass of air passing through 1 square foot of free area in front of the radiator.

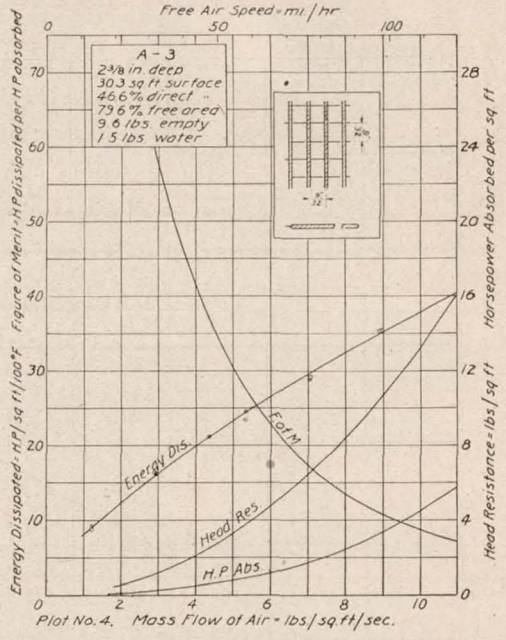
Radiator.	$c\times10^3$.	$k\times10^2$.	m	G	n	Radiator.	$c\times10^3$.	$k\times10^2$.	m	G	n
A–1	1.73	7.70	0.700	11.6	0.75	B–12	1.74	7.67	0.697	8.6	0.80
2	1.81	7.44	.676	11.8	.82	13	1.92	7.18	.653	8.9	.85
3	1.11	9.18	.834	7.6	.70						
4	1.48	8.75	.795	8.0	.75	C–1	2.07	5.81	.528	.....	.....
5	1.61	8.00	.727	9.9	.75	2	1.70	7.90	.718	8.7	.85
6	1.71	7.80	.709	10.2	.80	2a	1.85	6.31	.574	13.0	.60
7	1.86	7.34	.667	15.1	.75	2b	1.81	6.35	.577	15.0	.65
8	1.63	8.02	.729	7.5	.80	4	1.52	8.00	.727	7.1	.85
9	1.73	7.69	.699	9.8	.80	5	1.89	6.68	.607	9.0	.85
12	1.46	8.37	.761	8.4	.80	6	1.55	8.14	.740	9.3	.70
13	1.46	8.33	.757	8.4	.85	7	1.69	7.82	.711	8.3	.80
14	1.87	7.10	.645	13.0	.70	8	1.69	7.80	.710	8.2	.85
15	1.95	6.60	.600	8.4	.90	9	1.60	8.03	.730	8.0	.85
16	1.34	8.51	.774	7.5	.80	10	1.72	7.73	.703	8.3	.85
17	1.49	8.05	.732	8.7	.85						
18	1.14	8.80	.800	6.6	.60	D–1	1.32	8.03	.730	8.1	.70
19	1.40	8.18	.744	8.6	.85	2	1.98	5.27	.479	15.0	.70
20	1.80	7.01	.637	13.1	.85	3	2.31	5.98	.544	8.7	.85
21	1.54	7.64	.695	6.6	.85	4	1.64	8.03	.730	9.4	.70
22	1.55	7.59	.690	8.7	.85						
23	1.56	7.63	.694	10.3	.85	E–4	.....	.....	.....	10.2	.85
						6	1.74	7.07	.643	16.1	.80
B–1	1.11	9.21	.837	6.4	.63	7	1.16	8.35	.759	8.5	.90
2	1.24	8.91	.810	8.4	.60	8	.867	9.13	.830	7.6	.80
3	1.23	8.93	.812	5.9	.75	9	1.8	7.5	.68	9.1	1.00
4	1.75	7.60	.691	11.7	.65						
5	1.37	8.60	.782	6.5	.60	F–5	2.68	6.07	.552	10.0	.60
6	1.50	8.29	.754	9.5	.60						
7	1.70	7.77	.706	11.5	.60	G–1	2.57	5.39	.490	8.2	.60
8	1.91	7.07	.643	13.1	.60	2	2.05	7.21	.656	9.4	.65
9	1.85	7.37	.670	7.5	.85	3	2.40	6.25	.568	14.8	.75
10	1.64	7.92	.720	6.4	.85	4	2.29	.....	.....	12.7	.70
11	1.90	7.25	.659	8.0	.80						

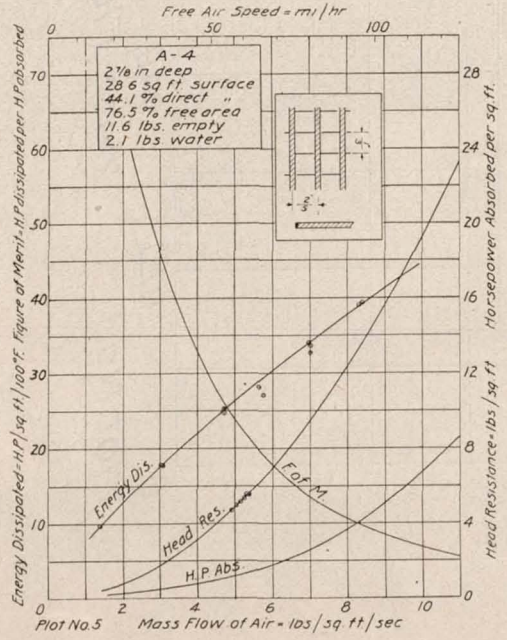


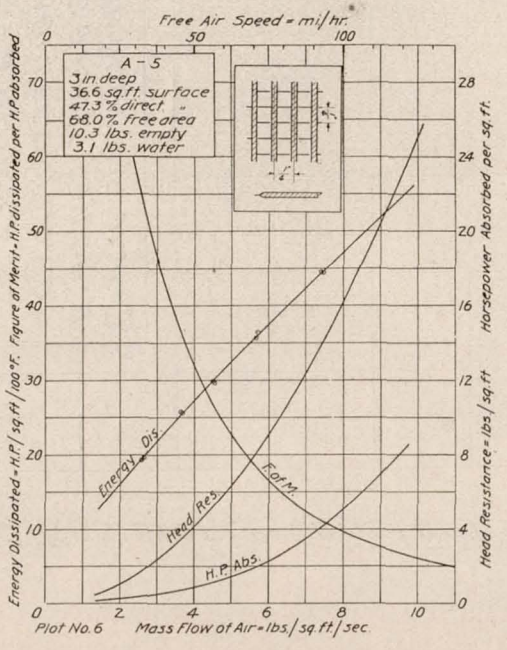
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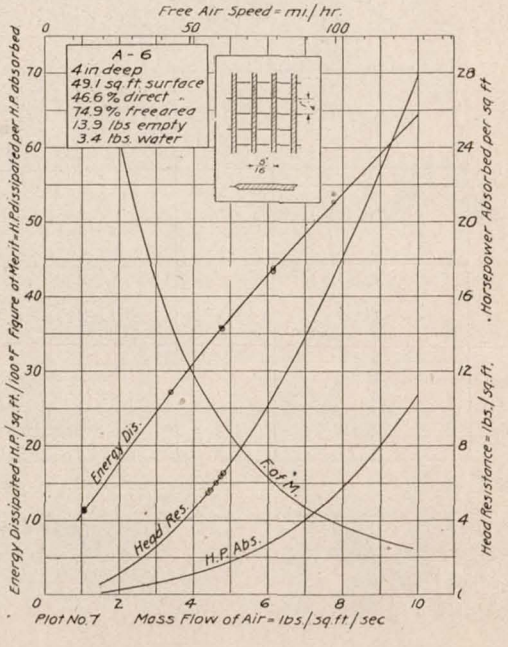

Free Air Speed = mi./hr.
A-1
3 in. deep
39.3 sq. ft. surface
44.0 % direct "
65.5 % free area
13.7 lbs. empty
2.1 " water
Energy Dis.
Head Res.
H.P. abs.
F of M
Energy Dissipated = H.P./sq. ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 2. Mass Flow of Air = lbs./sq. ft./sec

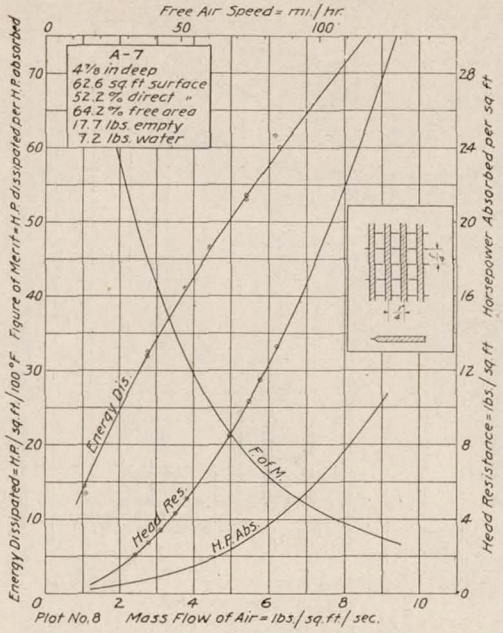

Free Air Speed = mi./hr.
A-2
3 7/8 in. deep
51.9 sq. ft. surface
44.0 % direct surface
65.7 % free area
18.3 lbs. empty
3.1 lbs. water
Energy Dis.
Head Res.
H.P. Abs.
F of M
Energy Dissipated = H.P./sq. ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 3. Mass Flow of Air = lbs./sq. ft./sec.

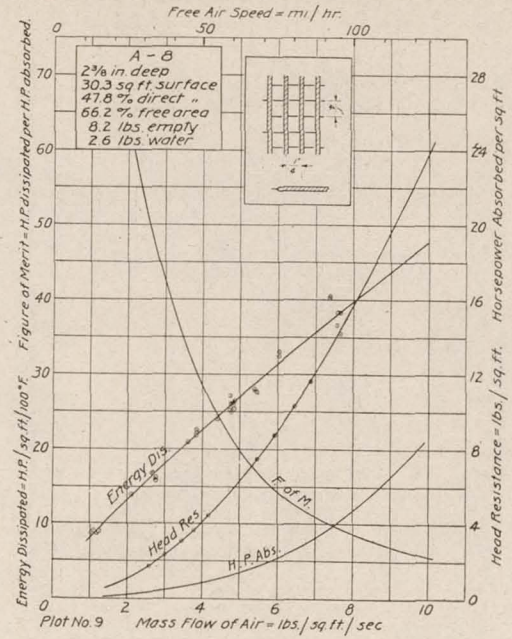

Free Air Speed = mi./hr.
A-3
2 3/8 in. deep
30.3 sq. ft. surface
46.6 % direct "
79.6 % free area
9.6 lbs. empty
1.5 lbs. water
Energy Dis.
Head Res.
H.P. Abs.
F of M
Energy Dissipated = H.P./sq. ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 4. Mass Flow of Air = lbs./sq. ft./sec.

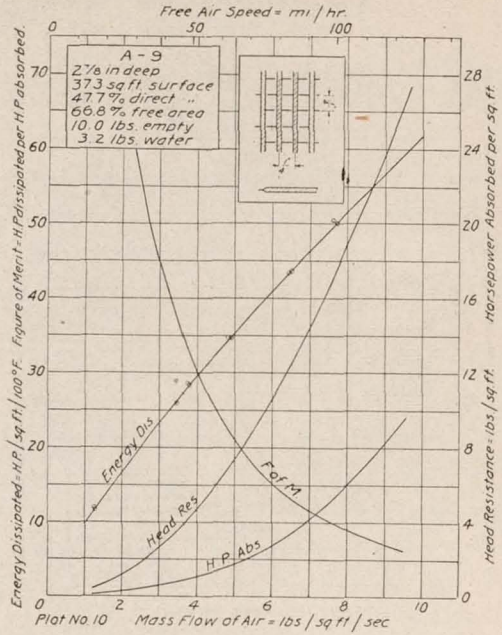

Free Air Speed = mi./hr.
A-4
2 1/8 in. deep
28.6 sq. ft. surface
44.1 % direct "
76.5 % free area
11.6 lbs. empty
2.1 lbs. water
Energy Dis.
Head Res.
H.P. Abs.
F of M
Energy Dissipated = H.P./sq. ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 5 Mass Flow of Air = lbs./sq. ft./sec

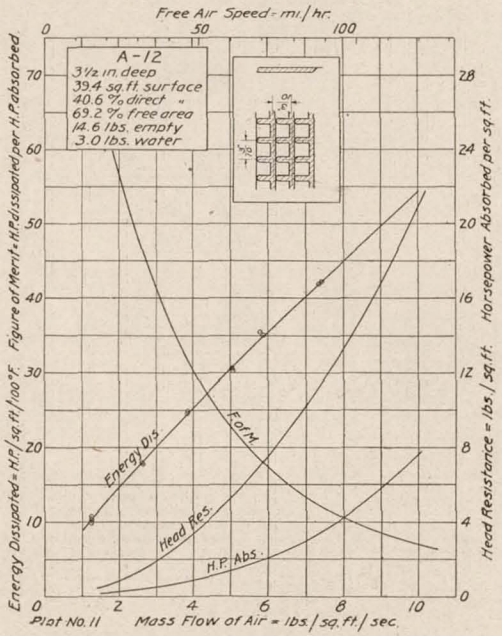

Free Air Speed = mi./hr.
A-5
3 in. deep
36.6 sq. ft. surface
47.3 % direct "
68.0 % free area
10.3 lbs. empty
3.1 lbs. water
Energy Dis.
Head Res.
H.P. Abs.
F of M
Energy Dissipated = H.P./sq. ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 6 Mass Flow of Air = lbs./sq. ft./sec.

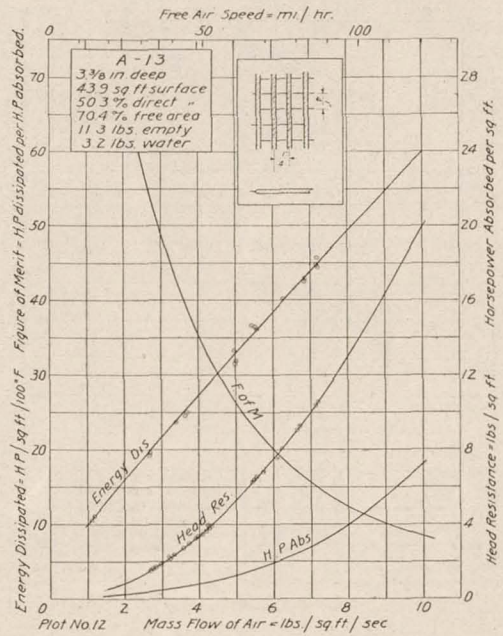

Free Air Speed = mi./hr.
A-6
4 in. deep
49.1 sq. ft. surface
46.6 % direct "
74.9 % free area
13.9 lbs empty
3.4 lbs. water
Energy Dis.
Head Res.
H.P. Abs.
F of M.
Energy Dissipated = H.P./sq. ft./100°F
Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq. ft.
Horsepower Absorbed per sq. ft.
Plot No. 7 Mass Flow of Air = lbs./sq. ft./sec

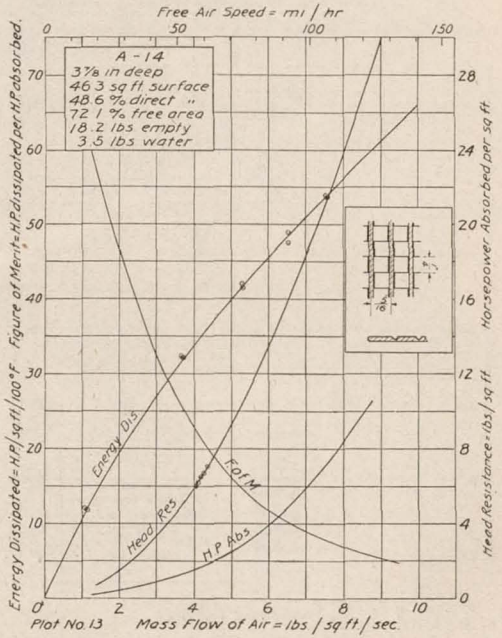

Free Air Speed = mi./hr.
A-7
4 7/8 in deep
62.6 sq ft surface
52.2 % direct "
64.2 % free area
17.7 lbs. empty
7.2 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq ft.
Plot No. 8
Mass Flow of Air = lbs./sq.ft./sec.

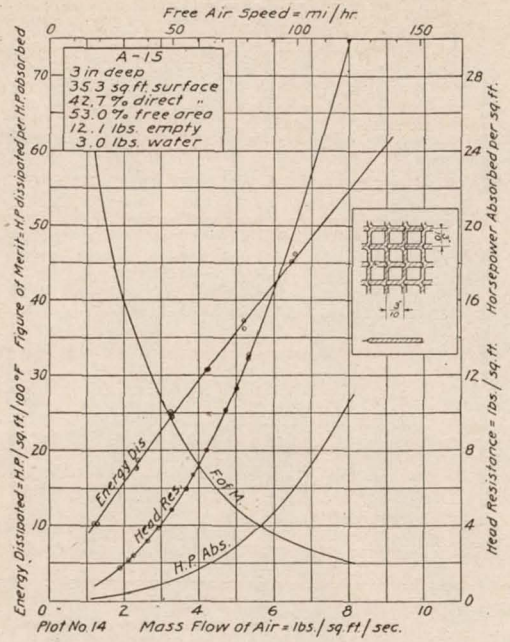

Free Air Speed = mi./hr.
A-8
2 3/8 in. deep
30.3 sq ft. surface
47.8 % direct "
66.2 % free area
8.2 lbs. empty
2.6 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq. ft.
Plot No. 9
Mass Flow of Air = lbs./sq.ft./sec

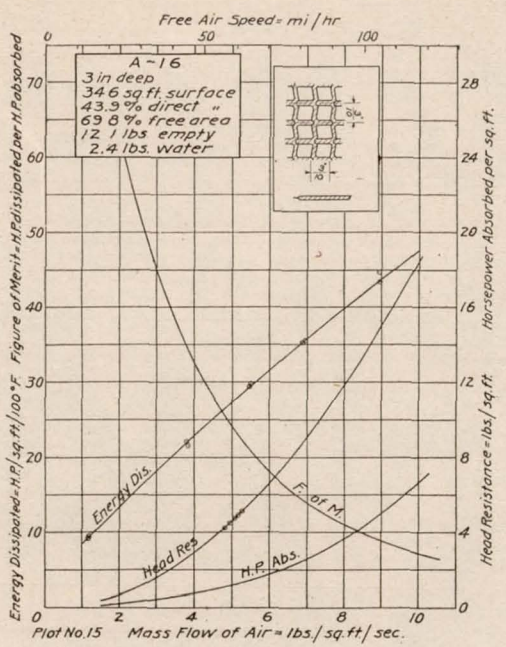

Free Air Speed = mi./hr.
A-9
2 7/8 in deep
37.3 sq ft surface
47.7 % direct "
66.8 % free area
10.0 lbs. empty
3.2 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq ft.
Plot No. 10
Mass Flow of Air = lbs./sq ft./sec

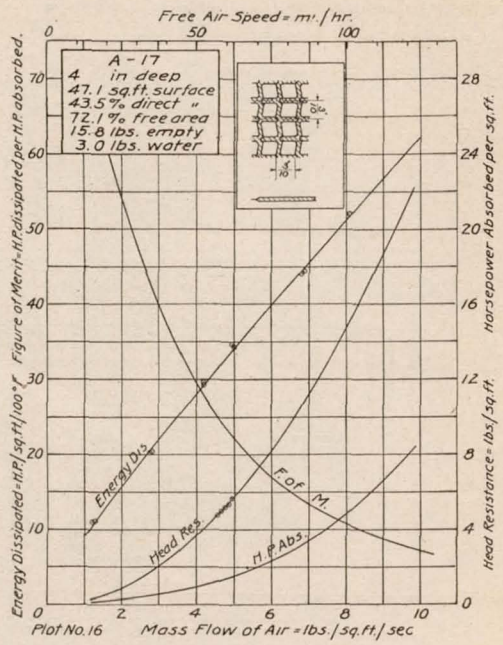

Free Air Speed = mi./hr.
A-12
3 1/2 in. deep
39.4 sq. ft. surface
40.6 % direct "
69.2 % free area
14.6 lbs. empty
3.0 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq. ft.
Plot No. 11
Mass Flow of Air = lbs./sq.ft./sec.

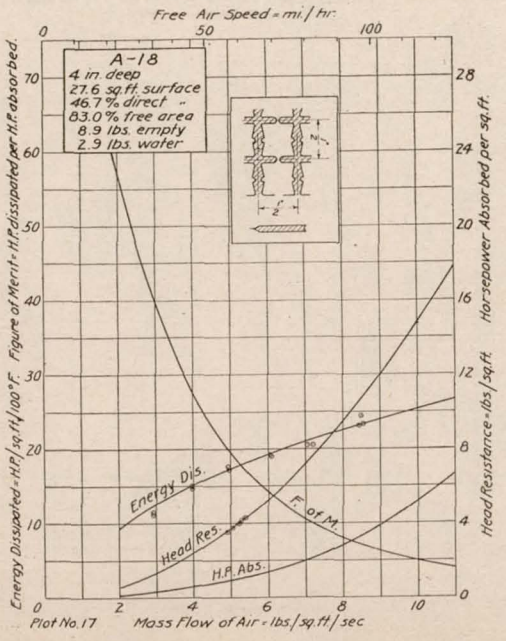

Free Air Speed = mi./hr.
A-13
3 3/8 in. deep
43.9 sq ft surface
50.3 % direct "
70.4 % free area
11.3 lbs. empty
3.2 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq. ft.
Plot No. 12
Mass Flow of Air = lbs./sq.ft./sec

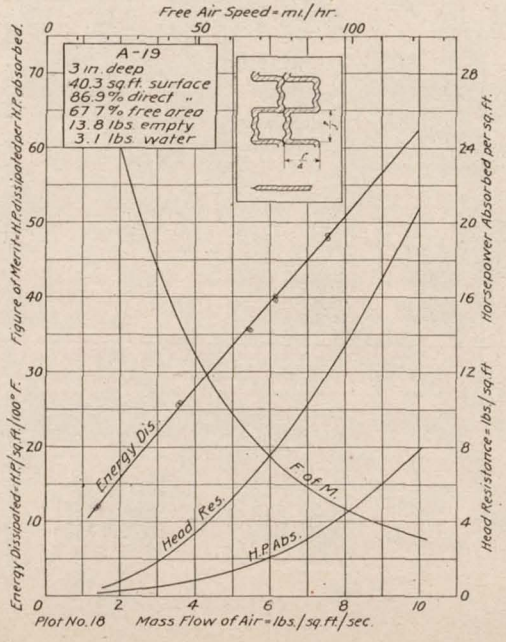

Free Air Speed = mi./hr.
A-14
3 7/8 in deep
46.3 sq ft surface
48.6 % direct "
72.1 % free area
18.2 lbs. empty
3.5 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq ft.
Head Resistance = lbs./sq ft.
Plot No. 13
Mass Flow of Air = lbs./sq ft./sec.

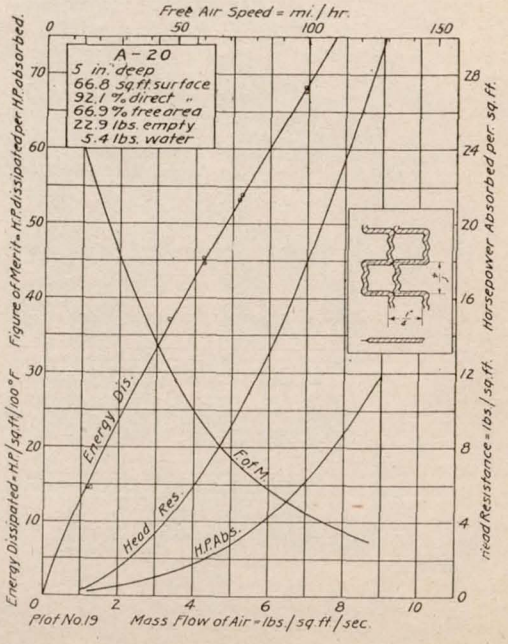

Free Air Speed = mi./hr.
A-15
3 in deep
35.3 sq.ft. surface
42.7% direct "
53.0% free area
12.1 lbs. empty
3.0 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 14 Mass Flow of Air = lbs./sq.ft./sec.

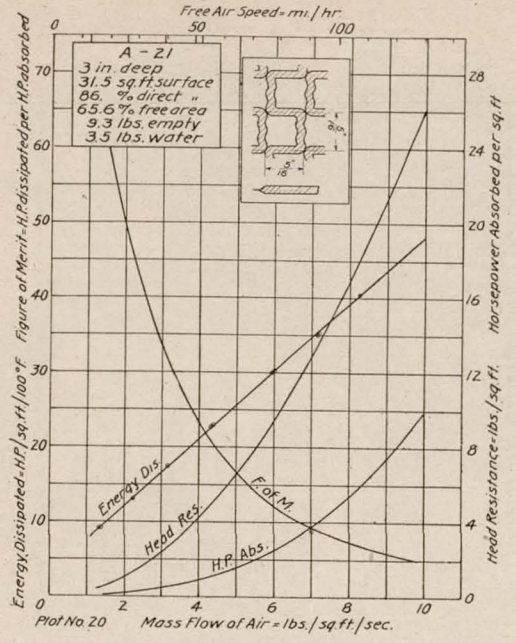

Free Air Speed = mi./hr.
A-16
3 in deep
34.6 sq.ft. surface
43.9% direct "
69.8% free area
12.1 lbs. empty
2.4 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 15 Mass Flow of Air = lbs./sq.ft./sec.

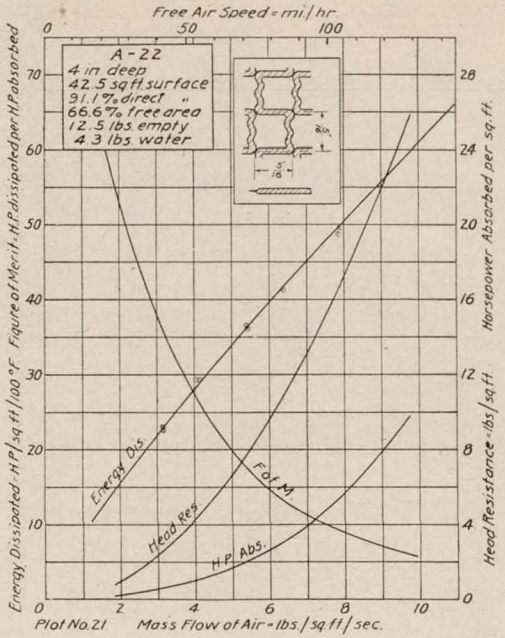

Free Air Speed = mi./hr.
A-17
4 in deep
47.1 sq.ft. surface
43.5% direct "
72.1% free area
15.8 lbs. empty
3.0 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 16 Mass Flow of Air = lbs./sq.ft./sec.

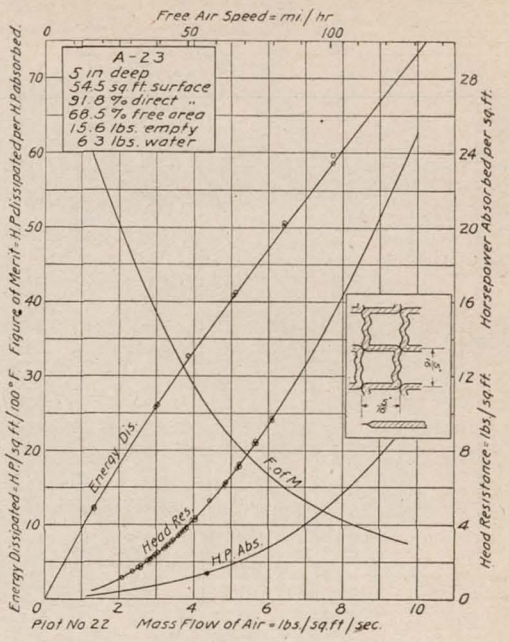

Free Air Speed = mi./hr.
A-18
4 in. deep
27.6 sq.ft. surface
46.7% direct "
83.0% free area
8.9 lbs. empty
2.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 17 Mass Flow of Air = lbs./sq.ft./sec.

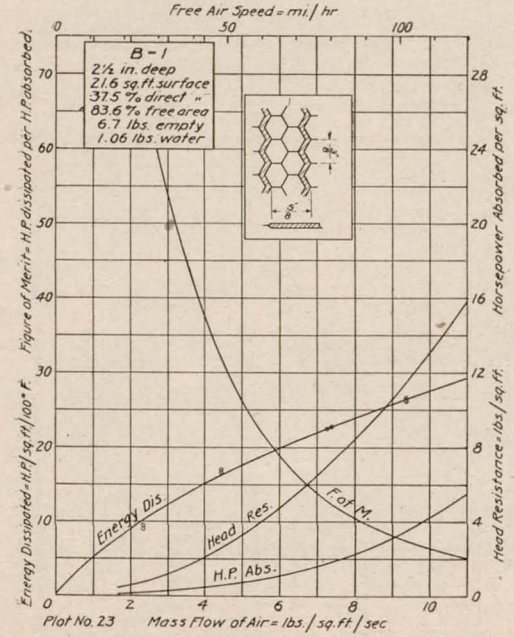

Free Air Speed = mi./hr.
A-19
3 in. deep
40.3 sq.ft. surface
86.9% direct "
67.7% free area
13.8 lbs. empty
3.1 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 18 Mass Flow of Air = lbs./sq.ft./sec.

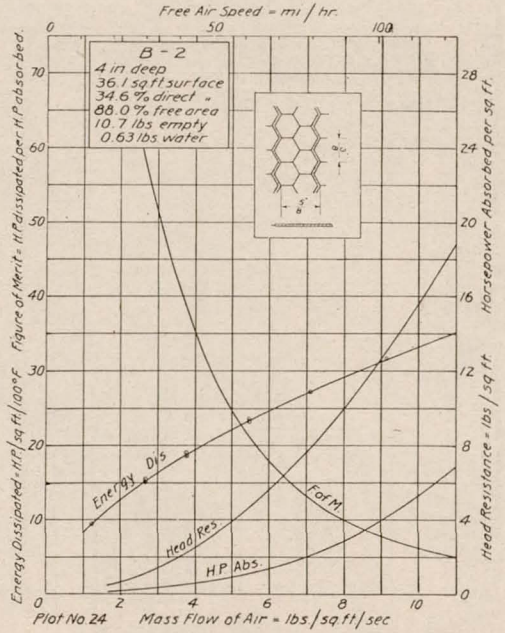

Free Air Speed = mi./hr.
A-20
5 in. deep
66.8 sq.ft. surface
92.1% direct "
66.9% free area
22.9 lbs. empty
5.4 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F. Figure of Merit = H.P. dissipated per H.P. absorbed
Head Resistance = lbs./sq.ft.
Horsepower Absorbed per sq.ft.
Plot No. 19 Mass Flow of Air = lbs./sq.ft./sec.

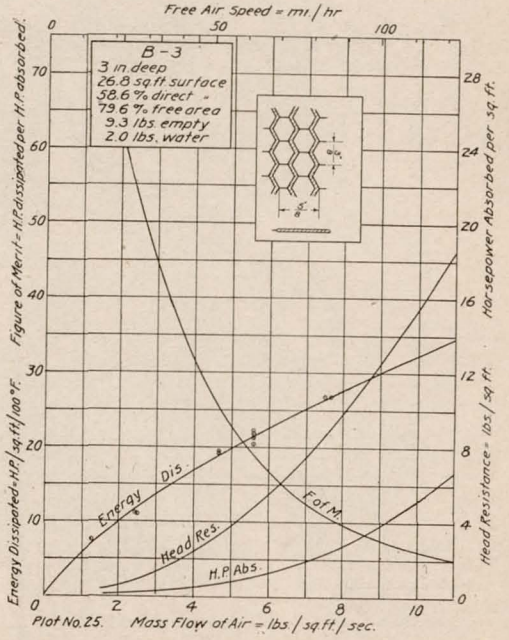

A - 21
3 in. deep
31.5 sq.ft.surface
86. % direct "
65.6% free area
9.3 lbs. empty
3.5 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 20
Mass Flow of Air = lbs./sq.ft./sec.

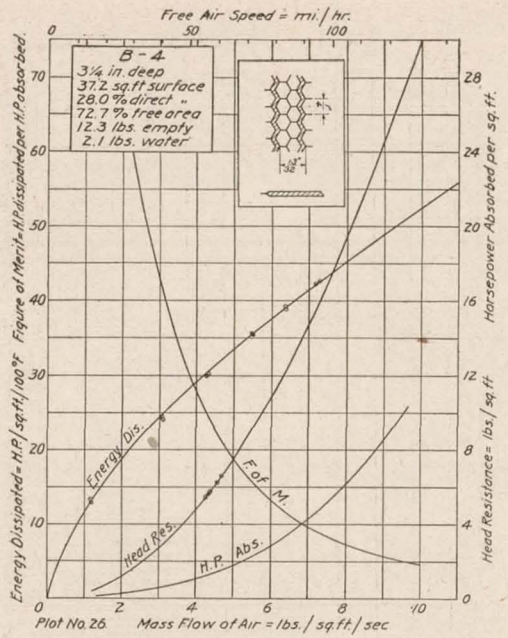

A - 22
4 in. deep
42.5 sq.ft.surface
91.1% direct "
66.6% free area
12.5 lbs. empty
4.3 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 21
Mass Flow of Air = lbs./sq.ft./sec.

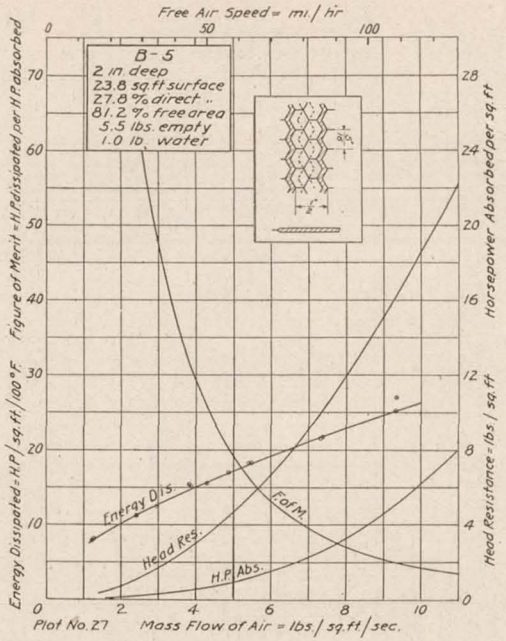

A - 23
5 in. deep
54.5 sq.ft.surface
91.8% direct "
68.5% free area
15.6 lbs. empty
6.3 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 22
Mass Flow of Air = lbs./sq.ft./sec.

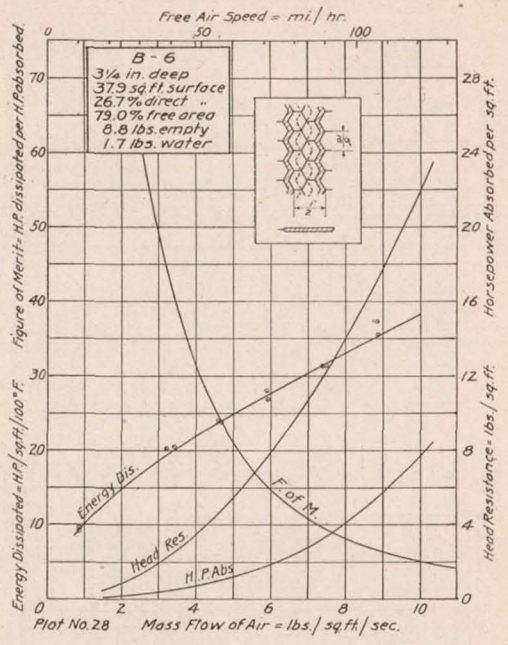

B - 1
2½ in. deep
21.6 sq.ft.surface
37.5% direct "
83.6% free area
6.7 lbs. empty
1.06 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 23
Mass Flow of Air = lbs./sq.ft./sec.

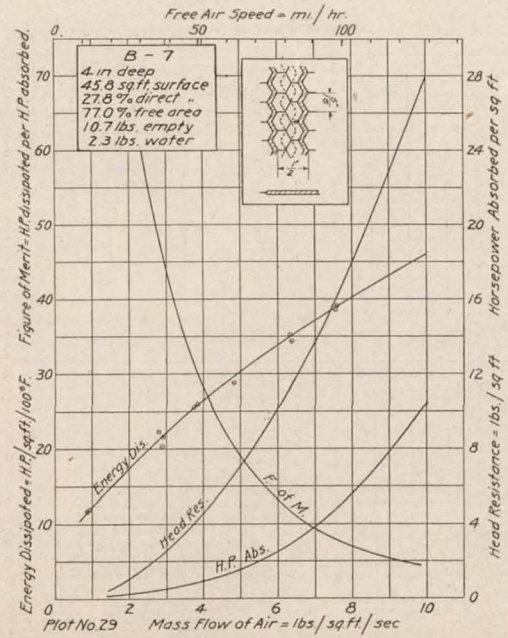

B - 2
4 in. deep
36.1 sq.ft.surface
34.6% direct "
88.0% free area
10.7 lbs. empty
0.63 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 24
Mass Flow of Air = lbs./sq.ft./sec

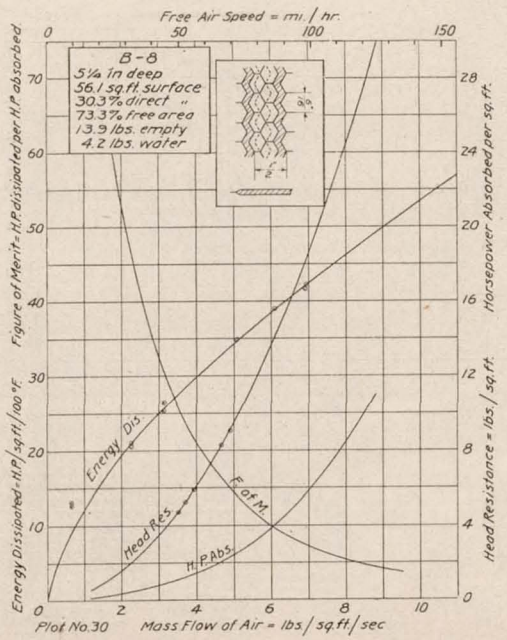

B - 3
3 in. deep
26.8 sq.ft.surface
58.6% direct "
79.6% free area
9.3 lbs. empty
2.0 lbs. water
Free Air Speed = mi./hr.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P.dissipated per H.P.absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Energy Dis.
Head Res.
H.P. Abs.
F. of M.
Plot No. 25.
Mass Flow of Air = lbs./sq.ft./sec.

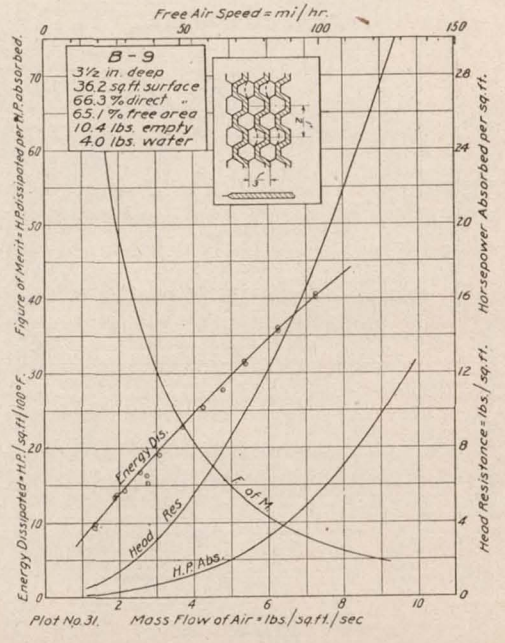

Free Air Speed = mi./hr.
B-4
3¼ in. deep
37.2 sq.ft. surface
28.0% direct ..
72.7% free area
12.3 lbs. empty
2.1 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 26
Mass Flow of Air = lbs./sq.ft./sec

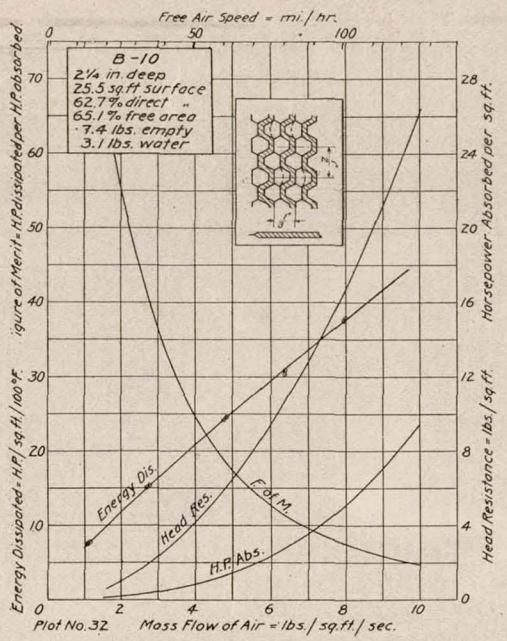

Free Air Speed = mi./hr.
B-5
2 in. deep
23.8 sq.ft. surface
27.8% direct ..
81.2% free area
5.5 lbs. empty
1.0 lb. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 27
Mass Flow of Air = lbs./sq.ft./sec.

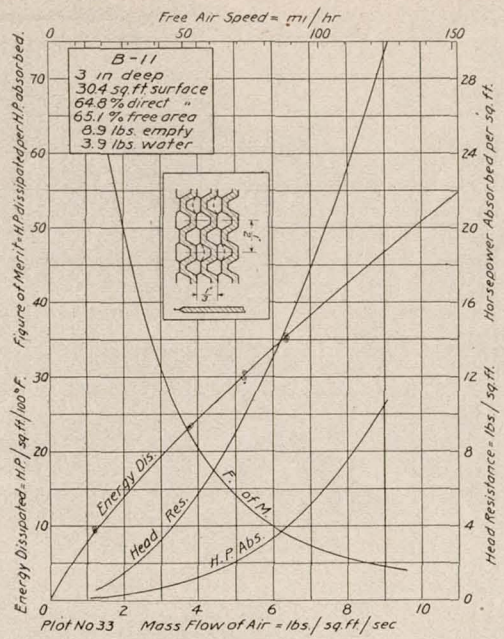

Free Air Speed = mi./hr.
B-6
3¼ in. deep
37.9 sq.ft. surface
26.7% direct ..
79.0% free area
8.8 lbs. empty
1.7 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 28
Mass Flow of Air = lbs./sq.ft./sec.

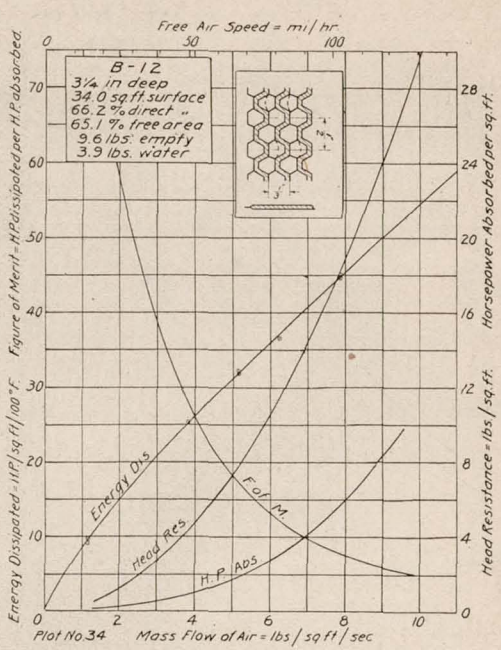

Free Air Speed = mi./hr.
B-7
4 in. deep
45.8 sq.ft. surface
27.8% direct ..
77.0% free area
10.7 lbs. empty
2.3 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 29
Mass Flow of Air = lbs./sq.ft./sec

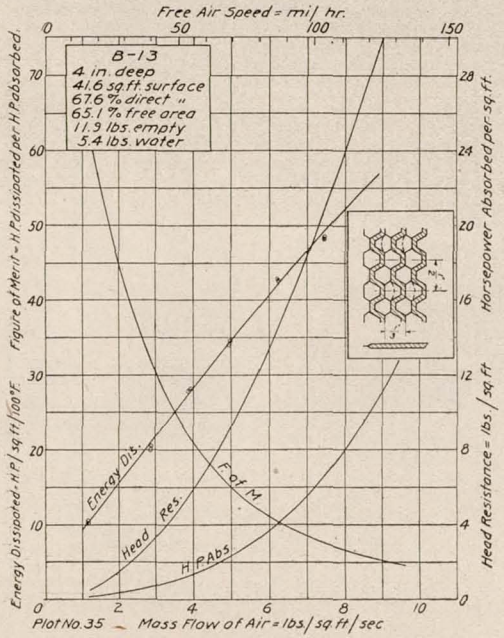

Free Air Speed = mi./hr.
B-8
5¼ in. deep
56.1 sq.ft. surface
30.3% direct ..
73.3% free area
13.9 lbs. empty
4.2 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 30
Mass Flow of Air = lbs./sq.ft./sec

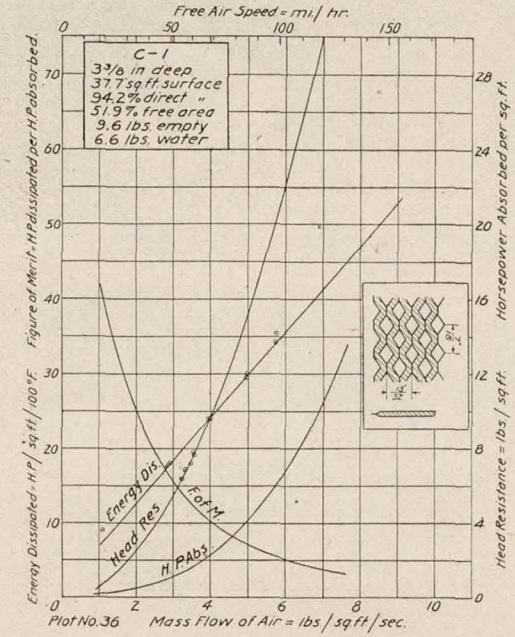

Free Air Speed = mi./hr.
B-9
3½ in. deep
36.2 sq.ft. surface
66.3% direct ..
65.1% free area
10.4 lbs. empty
4.0 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 31.
Mass Flow of Air = lbs./sq.ft./sec

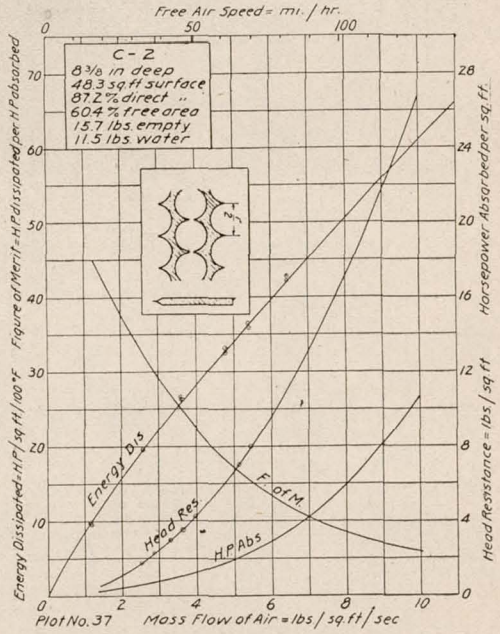

Free Air Speed = mi./hr.
B-10
2¼ in. deep
25.5 sq.ft surface
62.7% direct "
65.1% free area
7.4 lbs. empty
3.1 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 32
Mass Flow of Air = lbs./sq.ft./sec.

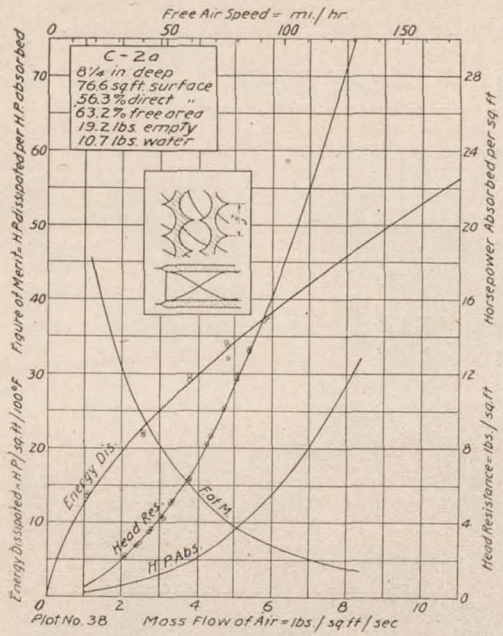

Free Air Speed = mi./hr.
B-11
3 in. deep
30.4 sq.ft surface
64.8% direct "
65.1% free area
8.9 lbs. empty
3.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 33
Mass Flow of Air = lbs./sq.ft./sec

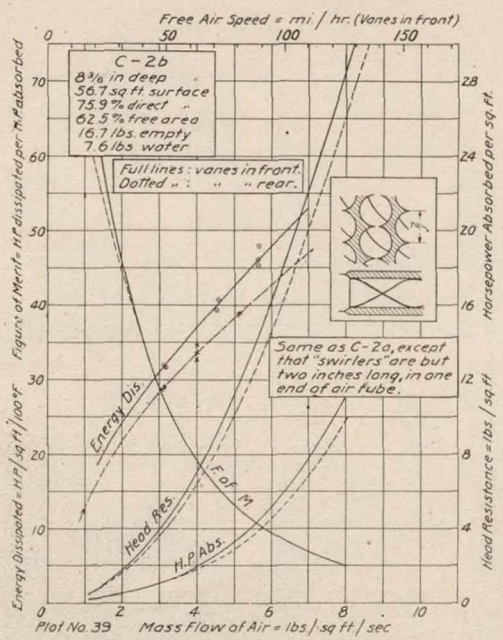

Free Air Speed = mi./hr.
B-12
3¼ in. deep
34.0 sq.ft surface
66.2% direct "
65.1% free area
9.6 lbs. empty
3.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 34
Mass Flow of Air = lbs./sq.ft./sec

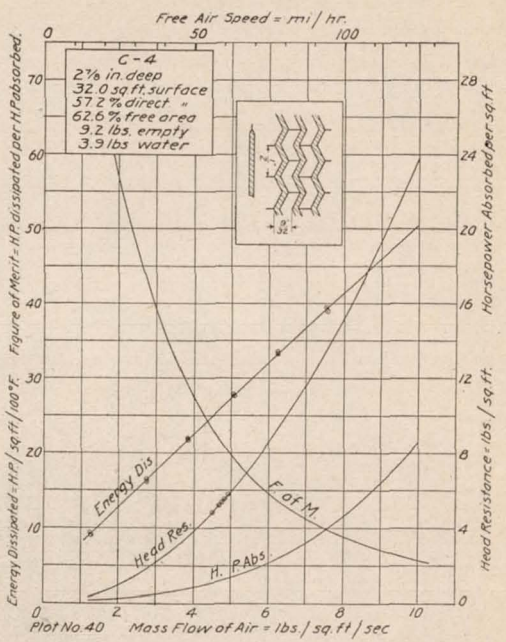

Free Air Speed = mi./hr.
B-13
4 in. deep
41.6 sq.ft. surface
67.6% direct "
65.1% free area
11.9 lbs. empty
5.4 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 35
Mass Flow of Air = lbs./sq.ft./sec

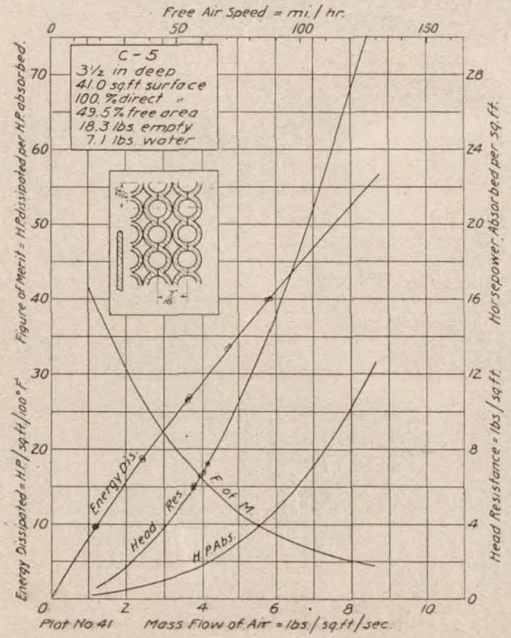

Free Air Speed = mi./hr.
C-1
3⅜ in. deep
37.7 sq.ft. surface
94.2% direct "
51.9% free area
9.6 lbs. empty
6.6 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 36
Mass Flow of Air = lbs./sq.ft./sec.

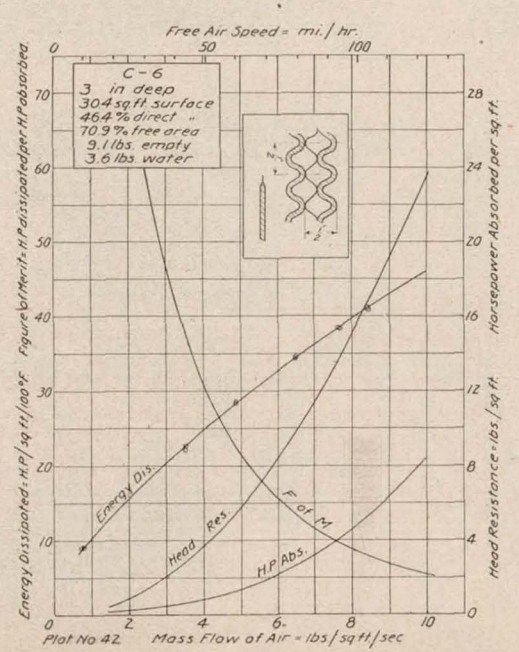

Free Air Speed = mi./hr.
C-2
8⅜ in. deep
48.3 sq.ft surface
87.2% direct "
60.4% free area
15.7 lbs. empty
11.5 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 37
Mass Flow of Air = lbs./sq.ft./sec

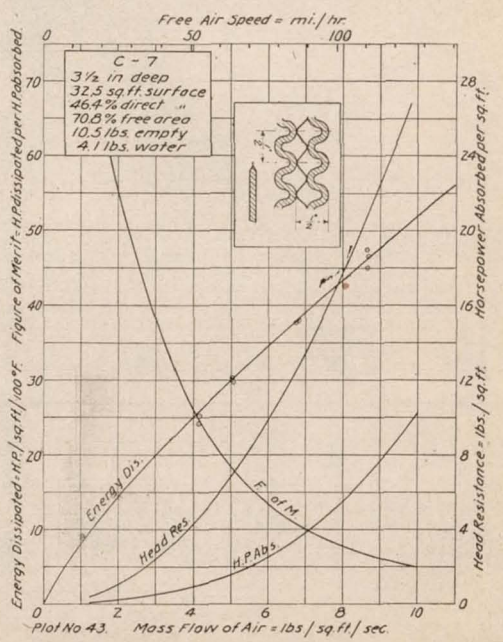

Free Air Speed = mi./hr.
C-2a
8¼ in deep
76.6 sq.ft. surface
56.3% direct "
63.2% free area
19.2 lbs. empty
10.7 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 38
Mass Flow of Air = lbs./sq.ft./sec

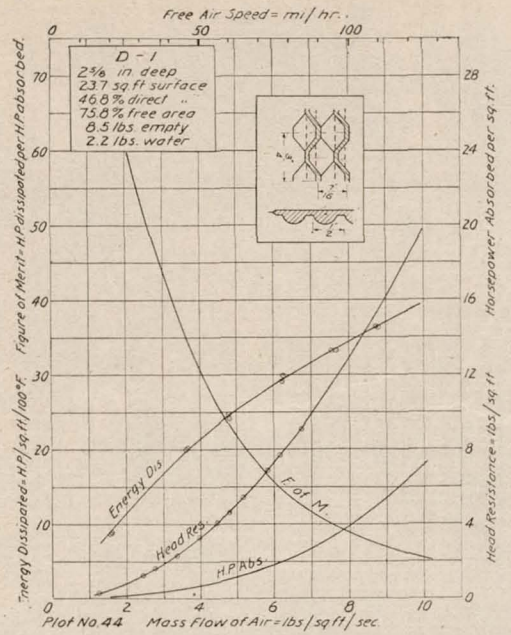

Free Air Speed = mi./hr. (Vanes in front)
C-2b
8⅜ in deep
56.7 sq.ft. surface
75.9% direct "
62.5% free area
16.7 lbs. empty
7.6 lbs. water
Full lines: vanes in front.
Dotted " : " " rear.
Same as C-2a, except that "swirlers" are but two inches long, in one end of air tube.
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 39
Mass Flow of Air = lbs./sq.ft./sec

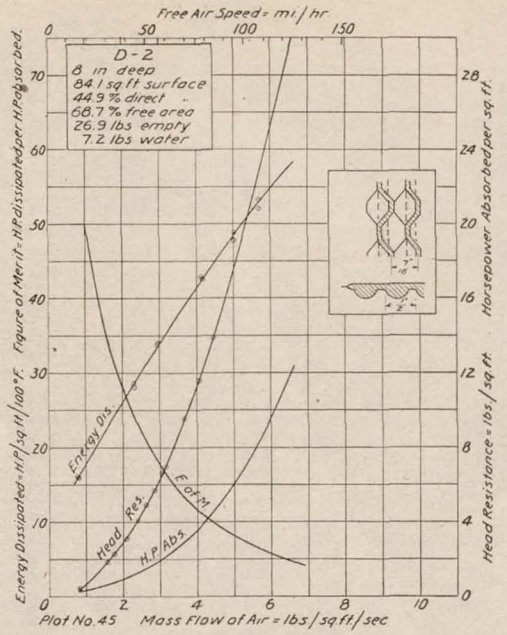

Free Air Speed = mi./hr.
C-4
2⅛ in. deep
32.0 sq.ft. surface
57.2% direct "
62.6% free area
9.2 lbs. empty
3.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 40
Mass Flow of Air = lbs./sq.ft./sec

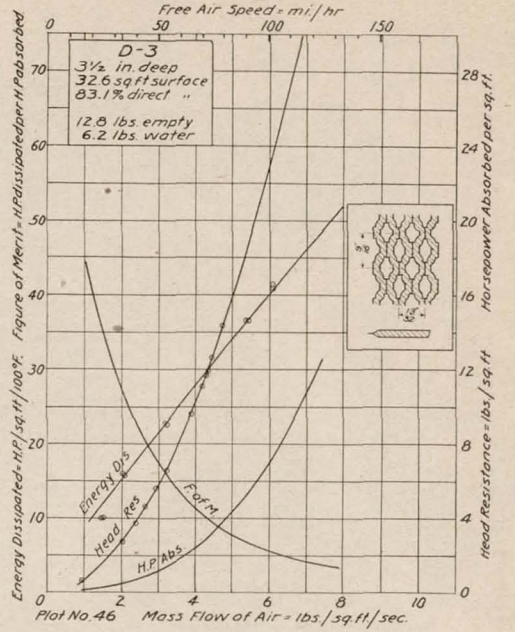

Free Air Speed = mi./hr.
C-5
3½ in deep
41.0 sq.ft. surface
100.% direct "
49.5% free area
18.3 lbs. empty
7.1 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 41
Mass Flow of Air = lbs./sq.ft./sec.

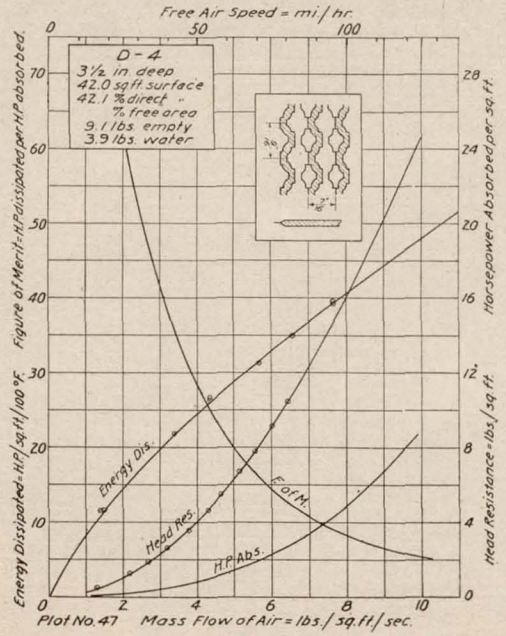

Free Air Speed = mi./hr.
C-6
3 in deep
30.4 sq.ft. surface
46.4% direct "
70.9% free area
9.1 lbs. empty
3.6 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 42
Mass Flow of Air = lbs./sq.ft./sec

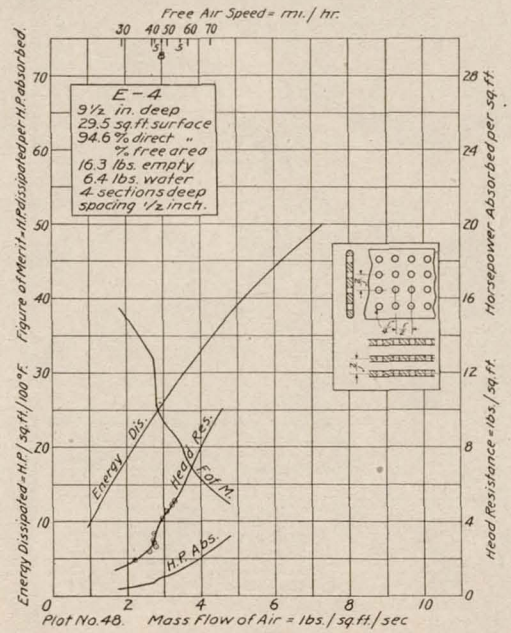

Free Air Speed = mi./hr.
C-7
3½ in deep
32.5 sq.ft. surface
46.4% direct "
70.8% free area
10.5 lbs. empty
4.1 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P.Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 43.
Mass Flow of Air = lbs./sq.ft./sec.

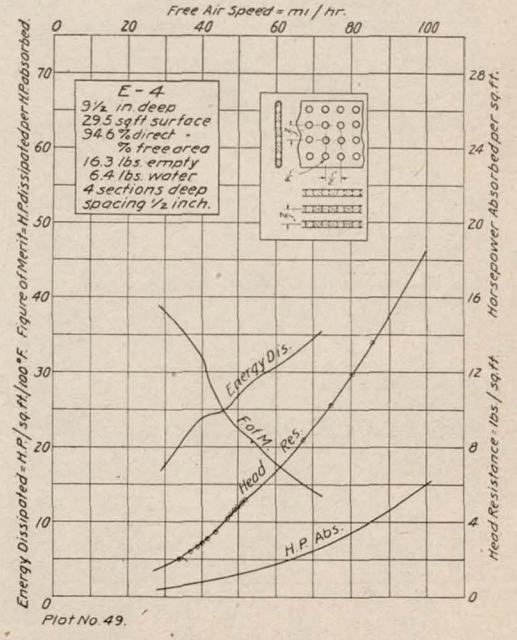

Free Air Speed = mi/hr.
D-1
2⅝ in. deep
23.7 sq.ft. surface
46.8% direct "
75.8% free area
8.5 lbs. empty
2.2 lbs. water
Energy Dis.
Head Res.
H.P Abs.
F. of M.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 44
Mass Flow of Air = lbs./sq.ft./sec.

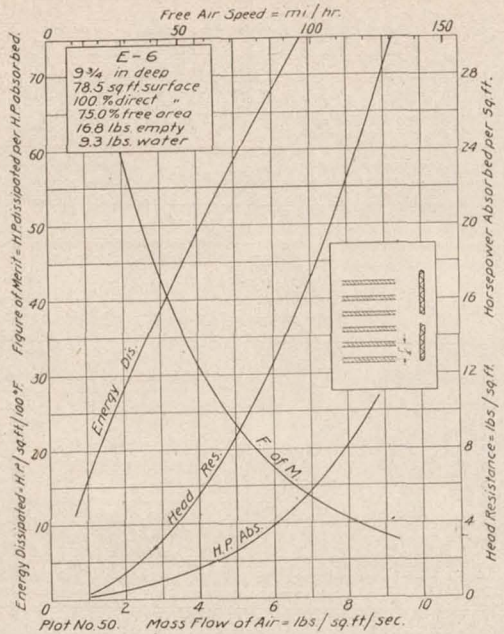

Free Air Speed = mi/hr.
D-2
8 in. deep
84.1 sq.ft. surface
44.9% direct "
68.7% free area
26.9 lbs. empty
7.2 lbs. water
Energy Dis.
Head Res.
H.P Abs.
F. of M.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 45
Mass Flow of Air = lbs./sq.ft./sec

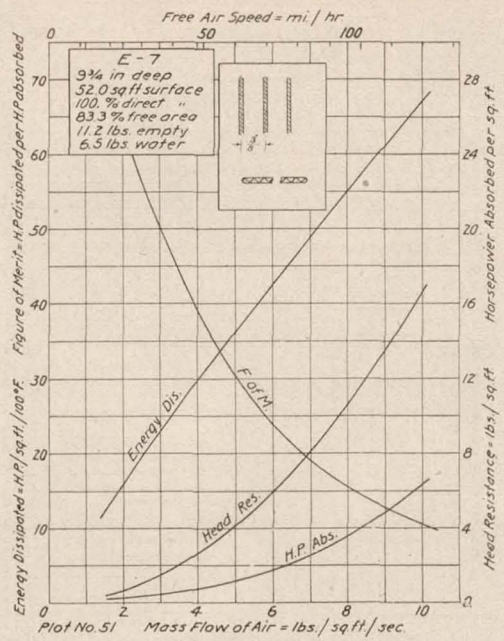

Free Air Speed = mi/hr.
D-3
3½ in. deep
32.6 sq.ft. surface
83.1% direct "
12.8 lbs. empty
6.2 lbs. water
Energy Dis.
Head Res.
H.P Abs.
F. of M.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 46
Mass Flow of Air = lbs./sq.ft./sec.

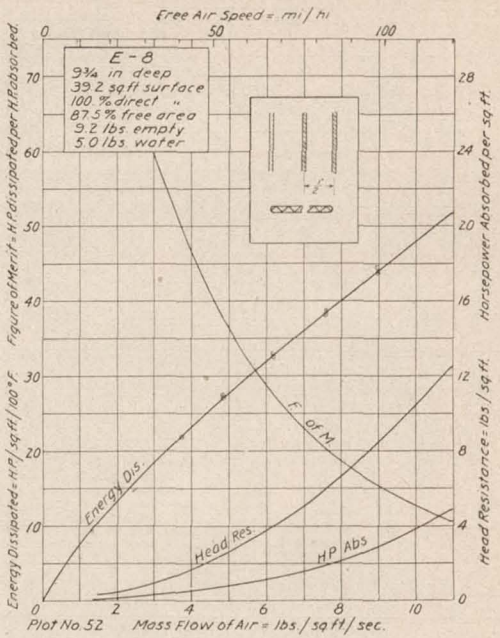

Free Air Speed = mi/hr.
D-4
3½ in. deep
42.0 sq.ft. surface
42.1 % direct "
% free area
9.1 lbs. empty
3.9 lbs. water
Energy Dis.
Head Res.
H.P Abs.
F. of M.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 47
Mass Flow of Air = lbs./sq.ft./sec.

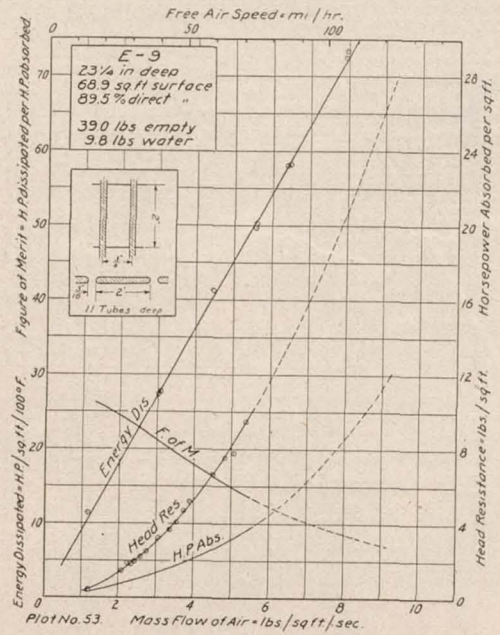

Free Air Speed = mi./hr.
E-4
9½ in. deep
29.5 sq.ft. surface
94.6% direct "
% free area
16.3 lbs. empty
6.4 lbs. water
4 sections deep
spacing ½ inch.
Energy Dis.
Head Res.
H.P Abs.
F. of M.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 48.
Mass Flow of Air = lbs./sq.ft./sec

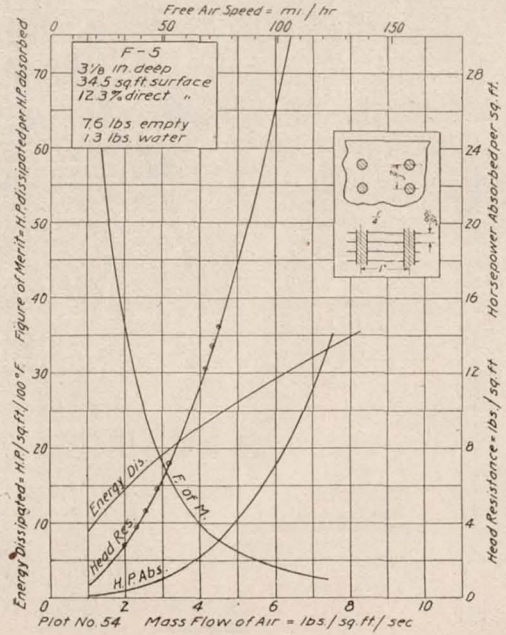

Free Air Speed = mi/hr.
E-4
9½ in. deep
29.5 sq.ft. surface
94.6% direct "
% free area
16.3 lbs. empty
6.4 lbs. water
4 sections deep
spacing ½ inch.
Energy Dis.
For M.
Res.
Head
H.P Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 49.

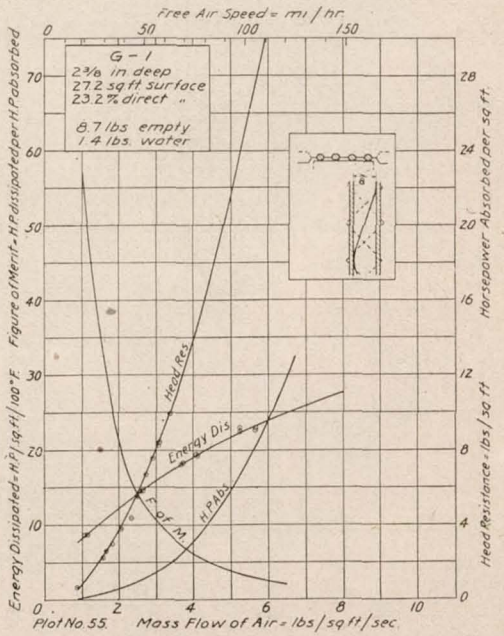

Free Air Speed = mi./hr.
E-6
9¾ in deep
78.5 sq ft surface
100.% direct "
75.0% free area
16.8 lbs. empty
9.3 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 50. Mass Flow of Air = lbs./sq.ft./sec.

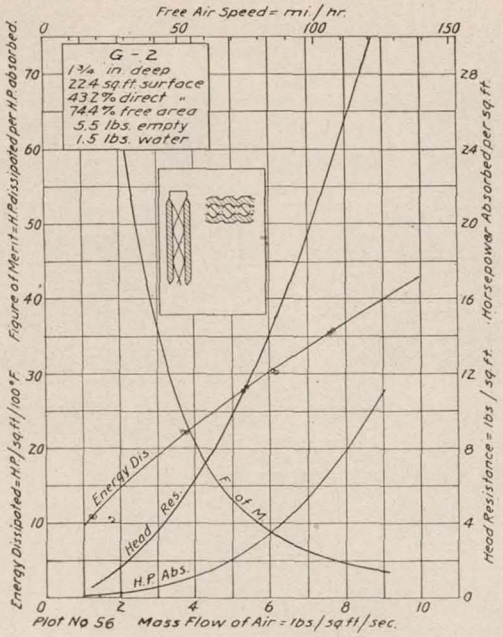

Free Air Speed = mi./hr.
E-7
9¾ in deep
52.0 sq ft surface
100.% direct "
83.3% free area
11.2 lbs. empty
6.5 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 51 Mass Flow of Air = lbs./sq.ft./sec.

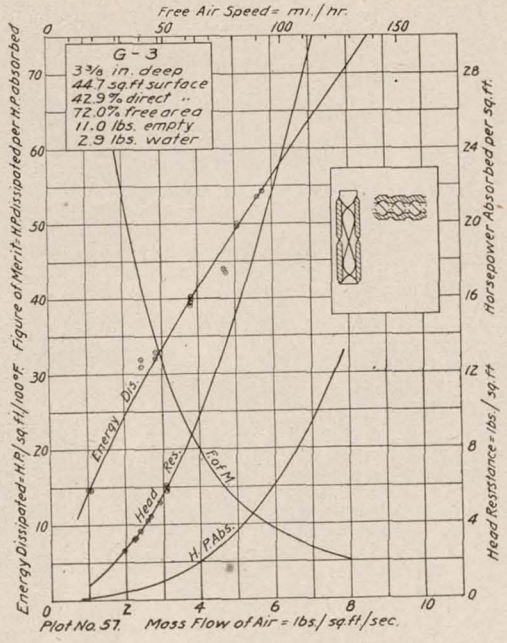

Free Air Speed = mi./hr.
E-8
9¾ in deep
39.2 sq ft surface
100.% direct "
87.5% free area
9.2 lbs. empty
5.0 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 52 Mass Flow of Air = lbs./sq.ft./sec.

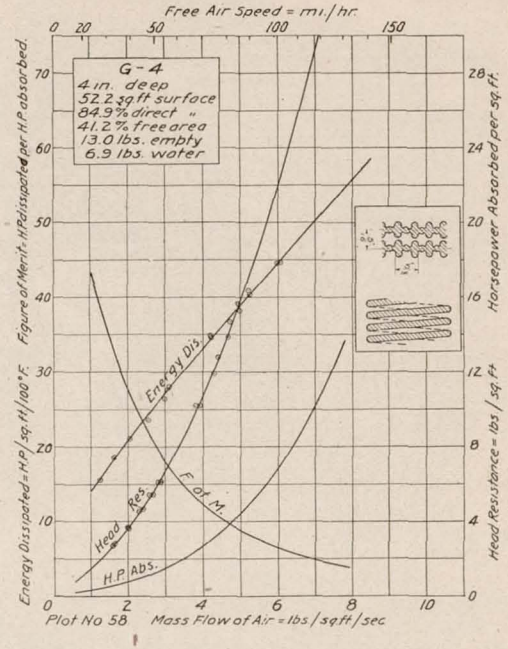

Free Air Speed = mi./hr.
E-9
23¼ in deep
68.9 sq ft surface
89.5% direct "
39.0 lbs. empty
9.8 lbs. water
11 Tubes deep
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 53. Mass Flow of Air = lbs./sq.ft./sec.

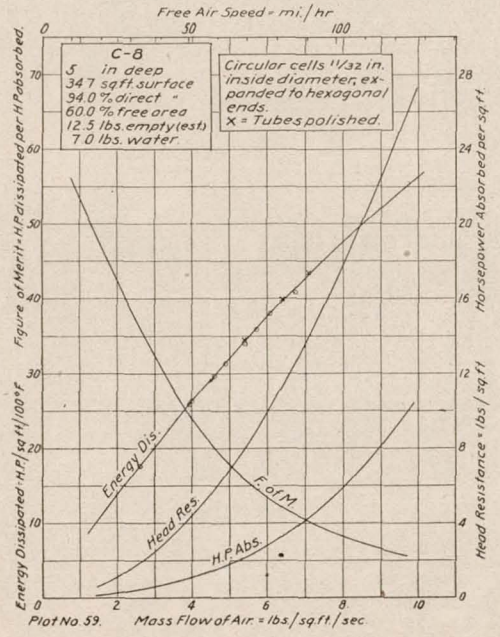

Free Air Speed = mi./hr.
F-5
3⅛ in. deep
34.5 sq ft surface
12.3% direct "
7.6 lbs. empty
1.3 lbs. water
Energy Dis.
F. of M.
Head Res.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 54 Mass Flow of Air = lbs./sq.ft./sec

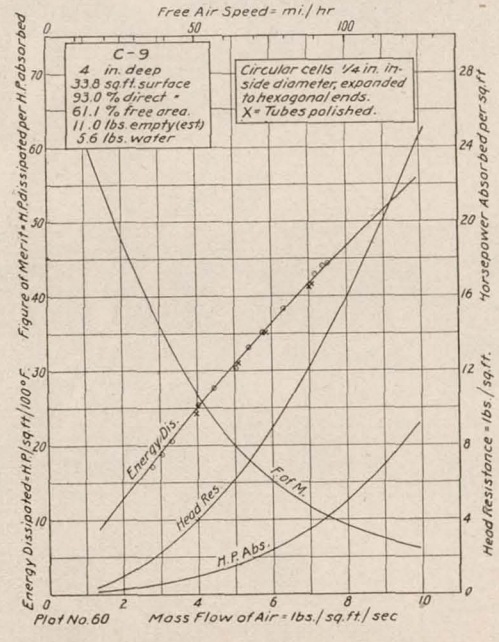

Free Air Speed = mi./hr.
G-1
2⅜ in deep
27.2 sq ft surface
23.2% direct "
8.7 lbs. empty
1.4 lbs. water
Head Res.
Energy Dis.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 55. Mass Flow of Air = lbs./sq.ft./sec.

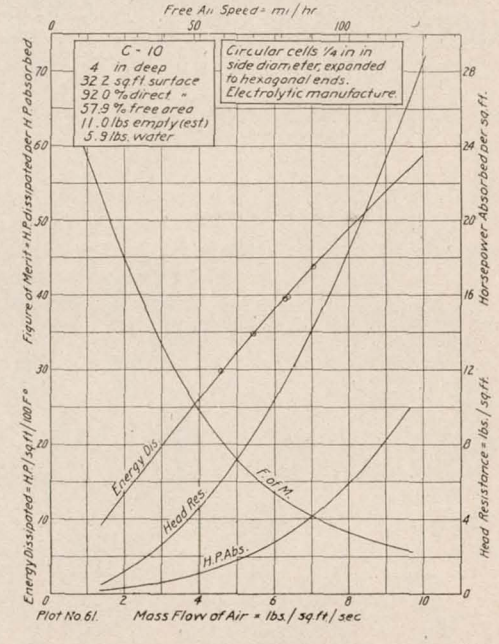

Free Air Speed = mi./hr.
G - 2
1¾ in. deep
22.4 sq.ft. surface
43.2% direct "
74.4% free area
5.5 lbs. empty
1.5 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No 56 Mass Flow of Air = lbs./sq.ft./sec.


Free Air Speed = mi./hr.
G - 3
3⅜ in. deep
44.7 sq.ft. surface
42.9% direct "
72.0% free area
11.0 lbs. empty
2.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 57. Mass Flow of Air = lbs./sq.ft./sec.


Free Air Speed = mi./hr.
G - 4
4 in. deep
52.2 sq.ft. surface
84.9% direct "
41.2% free area
13.0 lbs. empty
6.9 lbs. water
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No 58 Mass Flow of Air = lbs./sq.ft./sec.


Free Air Speed = mi./hr.
C-8
5 in. deep
34.7 sq.ft. surface
34.0% direct "
60.0% free area
12.5 lbs. empty (est)
7.0 lbs. water.
Circular cells 1 1/32 in. inside diameter, expanded to hexagonal ends.
X = Tubes polished.
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 59. Mass Flow of Air = lbs./sq.ft./sec.


Free Air Speed = mi./hr.
C-9
4 in. deep
33.8 sq.ft. surface
93.0% direct "
61.1% free area.
11.0 lbs. empty (est)
5.6 lbs. water
Circular cells ¼ in. inside diameter, expanded to hexagonal ends.
X = Tubes polished.
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 60 Mass Flow of Air = lbs./sq.ft./sec


Free Air Speed = mi./hr.
C - 10
4 in. deep
32.2 sq.ft. surface
92.0% direct "
57.9% free area
11.0 lbs. empty (est)
5.9 lbs. water
Circular cells ¼ in. inside diameter, expanded to hexagonal ends.
Electrolytic manufacture.
Energy Dis.
Head Res.
F. of M.
H.P. Abs.
Energy Dissipated = H.P./sq.ft./100°F.
Figure of Merit = H.P. dissipated per H.P. absorbed.
Horsepower Absorbed per sq.ft.
Head Resistance = lbs./sq.ft.
Plot No. 61. Mass Flow of Air = lbs./sq.ft./sec.

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REPORT No. 63.

PART II.

WATER FLOW THROUGH RADIATOR CORES.[1]

By W. S. James.

PURPOSE OF TESTS.

The tests were made to determine the pressure necessary to produce water flows up to 50 gallons per minute through an 8-inch square section of radiator core.

RADIATOR CORES TESTED.

The radiator cores tested were made up by the manufacturers in approximately 8-inch square sections and fitted with rectangular water boxes, as shown in figures 1 to 12. The makes and core depths of the sections tested were as follows:

(1) Ajax Auto and Aero Sheet Metal Co., ¼-inch square tubes, 4 inches deep.
(2) G. & O. Manufacturing Co., ¼-inch rhombic tubes, 3⅜ inches deep.
(3) The Harrison Radiator Corporation, $\frac{5}{16}$-inch hexagonal tubes, 4 inches deep.
(4) The Livingston Radiator & Manufacturing Co., ¼-inch square tubes, 4 inches deep.
(5) The Livingston Radiator & Manufacturing Co., $\frac{5}{16}$-inch square tubes, 4 inches deep.
(6) The Rome-Turney Radiator Co., ¼-inch square tubes, 3⅜ inches deep.
(7) The McCord Manufacturing Co., $\frac{5}{16}$-inch elliptical tubes, 3½ inches deep.
(8) The McCord Manufacturing Co., fin and tube, 3⅝ inches deep.
(9) The Modine Manufacturing Co., (Spirex core) $\frac{11}{16}$-inch square tube with spirals, 3½ inches deep.
(10) The Sparks-Withington Co., ⅜-inch elliptical tube, 3½ inches deep.
(11) The Hooven Sales Corporation, (Spery core) ⅝-inch elliptical tube, 2⅝ inches deep.
(12) The Western Mechanical Works, (Staggered core) $\frac{5}{16}$-inch staggered square tube, 4 inches deep.

METHOD OF TEST.

The radiator sections were connected in the discharge line of a centrifugal pump and in series with a Venturi meter. The discharge from the radiator was connected to the inlet of the pump. A reserve water tank in which a constant head of water was automatically maintained was connected to the suction line of the pump to provide a water reserve and to act as a surge tank. The centrifugal pump was driven by a belt from a direct current shunt motor.

The rate of water flow was measured by a Venturi meter with a 1-inch diameter inlet and a ½-inch diameter throat. The Venturi pressure difference was observed on a mercury gauge. The constant of the Venturi tube and gauge was determined by careful calibration. A constant pressure water supply from a pressure regulating valve was used as a source of water and the discharge was measured by means of a large weighing tank of about 100 cubic feet capacity.

The pressure drop in the water was measured by means of piezometer connections soldered on the radiator water boxes. These piezometer connections were made by soldering square copper tubes to the outside of the water boxes, then drilling from the outside one millimeter holes, spaced one inch apart, through both walls of the square copper tube and the water box top.

Holes were then bored in the water box ends and a scraping tool inserted in the water box to scrape off the burr on the holes inside the water boxes. A V-shaped strip of galvanized iron was then inserted in the water box to protect the holes from the effects of the impact of the high velocity water streams impinging on the piezometer tube holes. The holes in the

[1] This report was confidentially circulated during the war as Bureau of Standards Aeronautic Power Plants Report No. 3.

ends of the water boxes were then soldered up. The pressure difference between the two piezometer tubes was observed either on a long carbon-tetrachloride gauge or on a mercury gauge.

A general view of the set-up is given in figure 13. The pump is shown discharging through a control plug-cock, the Venturi meter tube and the radiator. The pressure drop and Venturi gauges can also be seen.

METHOD OF TAKING OBSERVATIONS.

In taking the observations the water level in the surge tank was adjusted to a constant height, then the pump was started and the air removed from the system by means of the air relief connections at the high points in the pressure connections. The rate of water flow was then adjusted to the desired value by means of the plug cock at the discharge of the pump. A small electric desk fan placed so as to force air through the radiator and thus keep the water cool was started and when the flow had reached a steady state six sets of readings were taken, three sets by each observer. The readings taken were (1) the reading of the Venturi meter gauge, (2) the reading of the pressure drop gauge, and (3) the temperature of the water in the system. When these observations were complete the rate of flow was adjusted to the next higher value and the readings repeated.

Table of water tube characteristics.

Radiator.	Area of each water tube.	Width of each water tube.	Thickness of each water tube.	Mean hydraulic radius of each water tube.	Length of each water tube parallel to direction of water flow.
	Square inch.	*Inch.*	*Inch.*	*Inch.*	*Inches.*
Ajax	0.125	3.65	0.034	0.0170	7.68
G. & O.	.226	2.91	.078	.0378	9.67
Harrison	.204	3.50	.058	.0287	9.02
Livingston $\frac{1}{4}$ inch	.0946	3.57	.027	.0138	15.97
Livingston $\frac{5}{16}$ inch	.132	3.57	.037	.0183	15.58
Rome-Turney	.156	3.00	.052	.0255	8.00
McCord fin and tube	.0433	.....	.0235	[a].0587	8.00
McCord elliptical	.244	3.02	.081	.0393	9.77
Spirex	.154	2.99	.052	.0254	8.75
Sparks-Withington	.320	3.07	.104	.0532	11.03
Spery	.173	2.29	.075	.0365	8.03
Staggered	.422	3.20	.132	.0634	7.88

[a] Diameter.

METHOD OF WORKING UP RESULTS.

The values of the rates of flow were computed in gallons per minute for each of the Venturi gauge readings at each rate of flow and the mean of these six readings taken as the mean rate of flow. The values of the pressure drop in the water were then computed from the six pressure drop gauge readings and the mean of these six readings was taken as the pressure drop corresponding to the measured rate of flow.

In this manner five points were obtained on the rate of flow-pressure drop curve for each radiator. The logarithms of the rates of flow were then plotted against the logarithms of the pressure drops and the observed points were found to lie on a straight line. Then as it was found that it was impossible to obtain greater flows than 25 gallons per minute with the set-up without bulging the water boxes of the radiators, the straight lines on the logarithmic plots were continued on to 50 gallons per minute. The anti-logarithms of the pressure drops were then found for points on the logarithmic curves corresponding to 30, 35, 40, 45, 50 and 55 gallons per minute. Plots 14 to 25 were then made by using the observed values of the pressure drop from 0 to 25 gallons per minute and the extrapolated values of the pressure drop from 25 to 55 gallons per minute found as indicated.

Because of the fact that the logarithmic plots gave straight lines it is evident that the observed results may be expressed by an empirical equation of the form

$$P = CQ^n$$

Where P is the pressure drop in feet of water, Q is the rate of flow in gallons per minute. C and n are constants. Values of n were found from the slopes of the logarithmic lines and are given on the plots for each radiator.

METHOD DEVISED FOR THE APPLICATION OF THE RESULTS OF THE ACCOMPANYING TESTS ON THE PRESSURE NECESSARY TO MAINTAIN WATER FLOW THROUGH RADIATOR CORES.

The following method of approximating the pressures necessary to maintain water flows through radiator cores has been devised in order to make immediate use of the data given in this report in estimating the order of magnitude of the pressure necessary to maintain water flows through radiator cores of dimensions (i. e., core lengths, widths, and depths) differing from those used in the experiments described.

Extreme accuracy can not be expected of the approximation given, the error being between 10 and 20 per cent. The terms width, length, and depth of the core as used in this report are defined as follows:

Core width is the linear dimension of the core, perpendicular to both the direction of water flow and the direction of air flow.

Core length is the linear dimension of the core, parallel to the direction of water flow.

Core depth is the linear dimension of the core, parallel to the direction of air flow.

METHOD OF USING PLOTS.

The method used is based upon the pressure necessary to maintain a given rate of flow the rough single water tubes 1 foot long and of varying depths of core (i. e., 3 inches, 3.5 inches, 4 inches, 4.5 inches, 5 inches, and 5.5 inches).

If all the water tubes in the radiator core carry equal amounts of water, the amount of water carried by each tube of any radiator section can be computed provided the following data are known: (1) The volume of water to be forced through the total width of core per minute, (2) the total width of radiator core the and (3) the number of water tubes per foot of width. The first two factors (1) and (2) are dependent on the design of the radiator in question, the latter (3) is given on plots 26 to 37 for the cores tested.

When the amount of water to be carried by each tube has been determined the pressure necessary to maintain the required rate of flow can be read from the plots which gives the pressures necessary to maintain various rates of flow through a single water tube 1 foot in length of the make of radiator core indicated. On these plots curves are drawn for even one-half inch depths of core from 3 to 5.5 inches. The pressure corresponding to the flow desired may be read from the curve for the core depth to be used or found by estimation between the curves for the core depths given.

The pressure found from the plot is then multiplied by the length of the radiator core in the direction of water flow. The product of the pressure necessary to maintain the desired flow through 1 foot length of radiator core multiplied by the core length will give the approximate value of the pressure required to maintain the desired rate of water flow.

For example: It is desired to find the pressure necessary to maintain a water flow of 100 gallons per minute through a "Spery" radiator core 32 inches long, 16 inches wide, and 4 inches deep.

As there are 30 water tubes per foot width of core, there are 40 tubes per 16 inches of width.

The rate of flow through each tube will therefore be $\frac{100}{40} = 2.5$ gallons per tube per minute.

From the plot, a pressure of 10.7 feet of water per foot of tube length is required to maintain a flow of 2.5 gallons per minute per tube.

As the tube length is 2.5 feet, a pressure of $2.5 \times 10.7 = 27$ feet of water will be required to maintain a flow of 100 gallons of water per minute through the "Spery" core 16 inches wide and 32 inches long.

METHOD OF CONSTRUCTING PLOTS.

The following method was adopted in constructing the plots of the pressures necessary to produce given rates of water flow through single tubes 1 foot long with varying depths.

Values of the pressure necessary to maintain rates of flow of 10, 20, 30, 40, and 50 gallons per minute through an 8-inch width of core were read from the plot for each type of radiator

tested. These values of the pressure necessary for an 8-inch core were multiplied by 1.5 to reduce them to the value for a core length of 1 foot. The various rates of flow (i. e., 10, 20, 30, 40, and 50 gallons per minute) were then divided by the number of tubes and the corresponding values of the flow in gallons per tube found.

The Chezy formula for water flow was then assumed in the form given below (1) and the effect on the value of $\triangle P$ of changing core depths found for the rates of flow indicated above as follows:

V = Linear water velocity.
$\triangle P$ = Pressure necessary to maintain velocity V.
R = Hydraulic radius of water tube.
$= \frac{\text{Area of water tube}}{\text{Perimeter of water tube.}}$
A = Area of water tube.
Q = Rate of water flow.
t = Water tube thickness.
d = Water tube depth.
n & c = constants.

$$V = C\,(R\triangle P)^{\frac{1}{n}} \tag{1}$$

Now $Q = AV$, $A = td$, and $R = \frac{td}{2(t+d)}$.

Substitution of these values in (1) gives,

$$Q = Ctd\left[\frac{\triangle P}{2} \times \frac{td}{t+d}\right]^{\frac{1}{n}}$$

$$\triangle P = \frac{2Q^n}{C^n} \times \frac{t+d}{(td)^{n+1}},$$

so that

$$\frac{\triangle P_1}{\triangle P_2} = \frac{(t_1+d_1)(t_2d_2)^{n+1}}{(t_2+d_2)(t_1d_1)^{n+1}}.$$

Since $t_1 = t_2$, we have

$$\triangle P_1 = \triangle P_2\left(\frac{d_2}{d_1}\right)^{n+1}\left(\frac{t_1+d_1}{t_2+d_2}\right). \tag{2}$$

Equation (2) provides a means of evaluating $\triangle P$ for a core 3 inches, 3.5 inches, 4 inches (etc.) deep when the value of $\triangle P$ for a core "d" inches deep "t" inches thick and the exponent "n" are known.

When the values of $\triangle P$ for various core depths are found in the manner indicated above and are read directly from the curves plotted, the following assumptions have been tacitly made:

(1) That the same quantity of water passes through each water tube in the core.

(2) That the pressure maintaining flow varies directly as the length of the water tube parallel to the direction of water flow, and that the entrance and exit losses are neglected.

(3) That the pressure necessary to produce flow varies inversely as the hydraulic radius and directly as the "nth" power of the linear water velocity. The values of "n" being found by experiment when the hydraulic radius remains constant.

(4) That the water tube thickness remains constant for any given core and has the value given, when the depth of the core and the length of the water path change.

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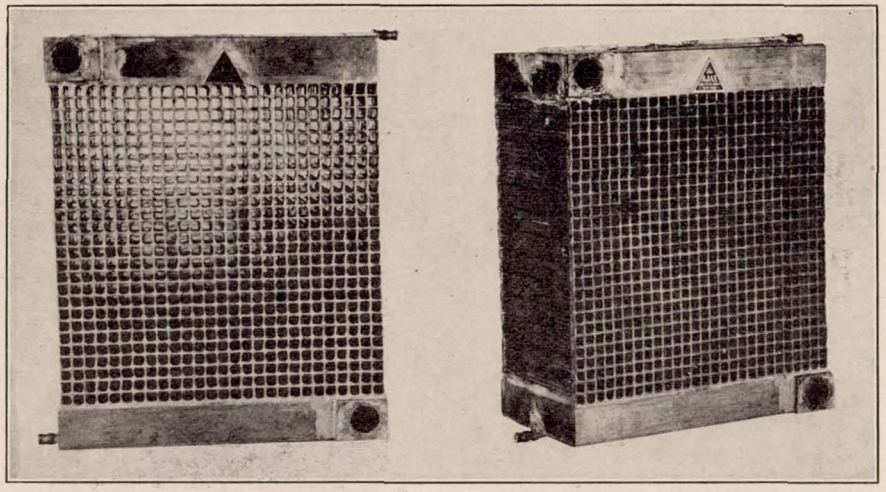


FIGURE 1.—Ajax Auto and Aero Sheet Metal Co. ½-inch square tubes. Core 4 inches deep.

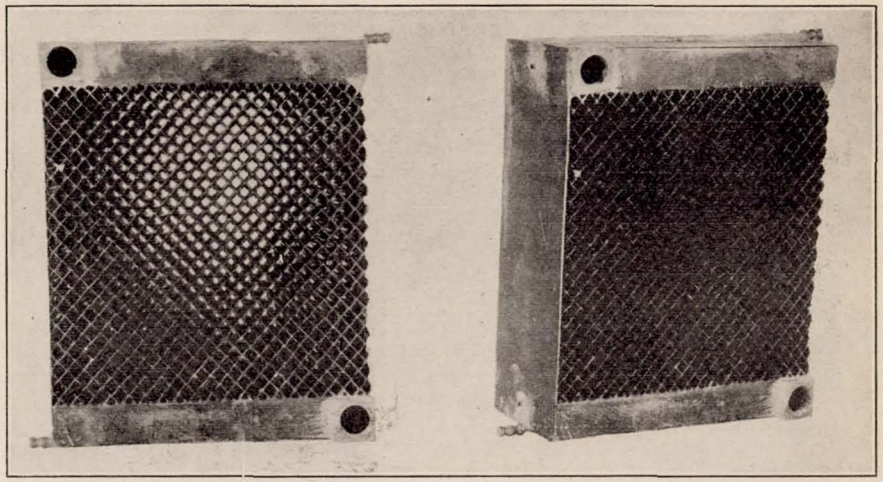


FIGURE 2.—G. & O. Manufacturing Co. ½-inch rhombic tubes. Core 3⅜ inches deep.

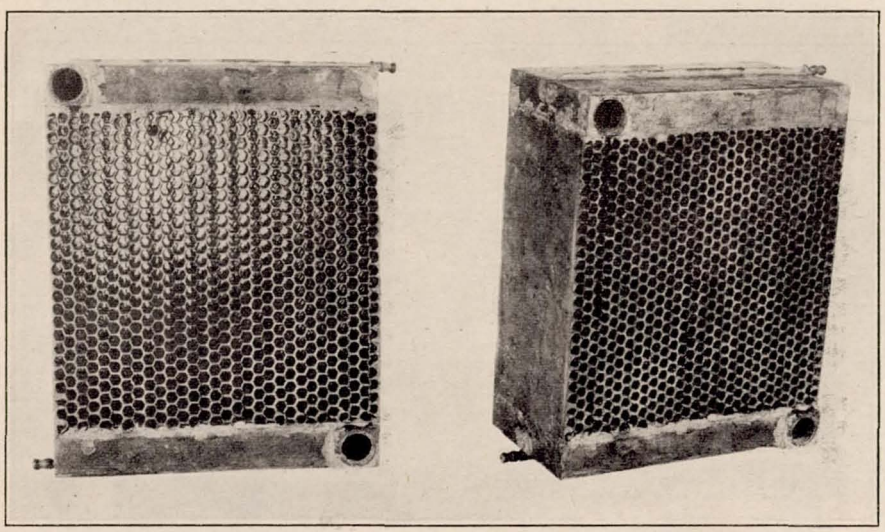


FIGURE 3.—The Harrison Radiator Corporation. $\frac{5}{16}$-inch hexagonal tubes. Core 4 inches deep.

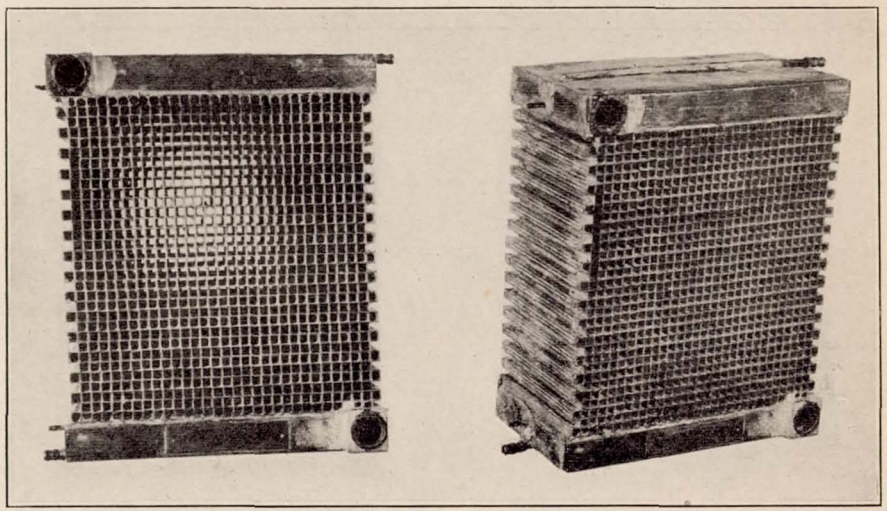


FIGURE 4.—The Livingston Radiator & Manufacturing Co. ½-inch square tube. Core 4 inches deep.

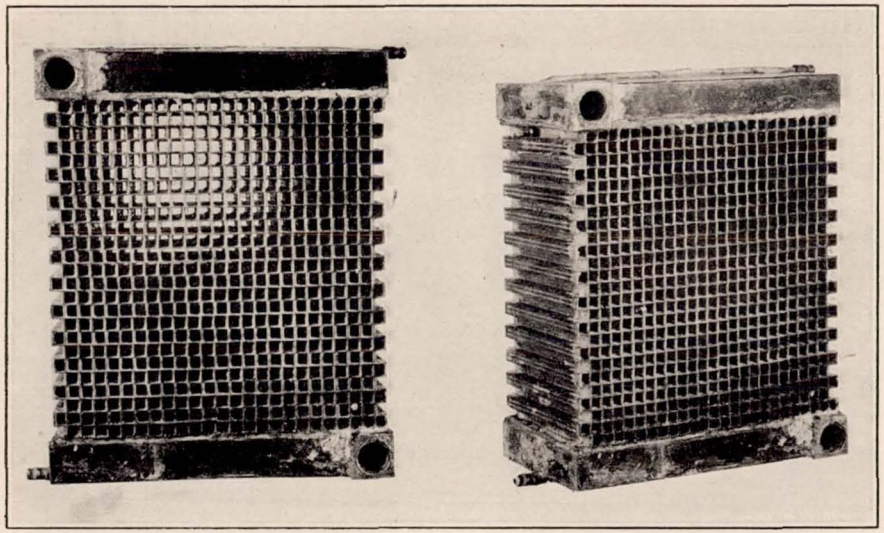


FIGURE 5.—The Livingston Radiator & Manufacturing Co. $\frac{5}{16}$-inch square tubes. Core 4 inches deep.

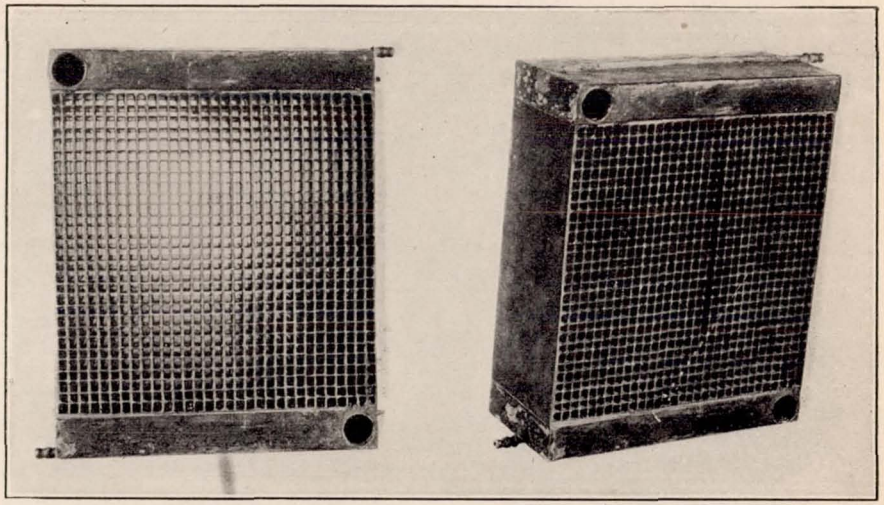


FIGURE 6.—The Rome-Turney Radiator Co. $\frac{1}{4}$-inch square tubes. Core $3\frac{3}{8}$ inches deep.

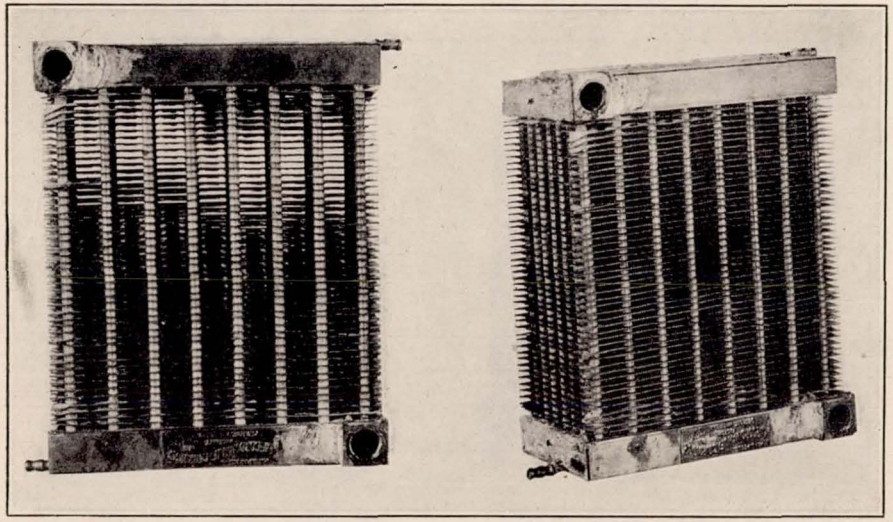


FIGURE 7.—The McCord Manufacturing Co. Fin and tube. Core $3\frac{3}{8}$ inches deep.

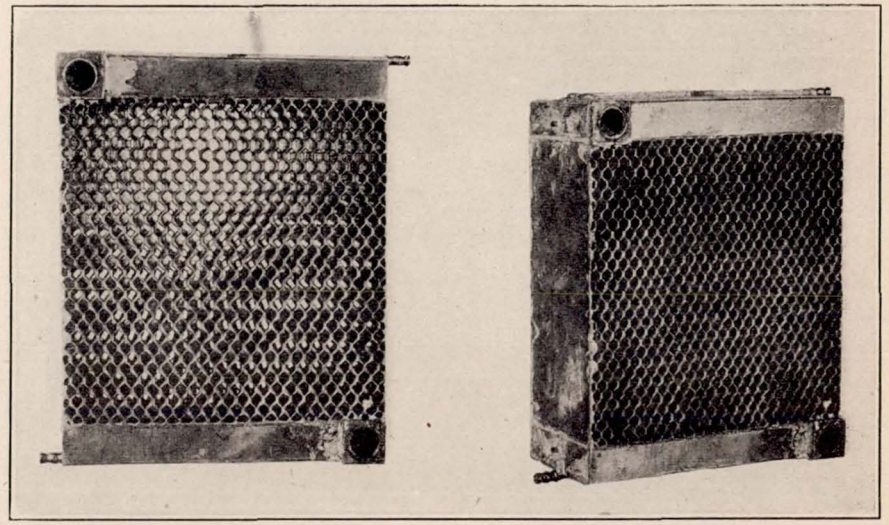


FIGURE 8.—The McCord Manufacturing Co. $\frac{5}{16}$-inch elliptical tubes. Core $3\frac{1}{2}$ inches deep.

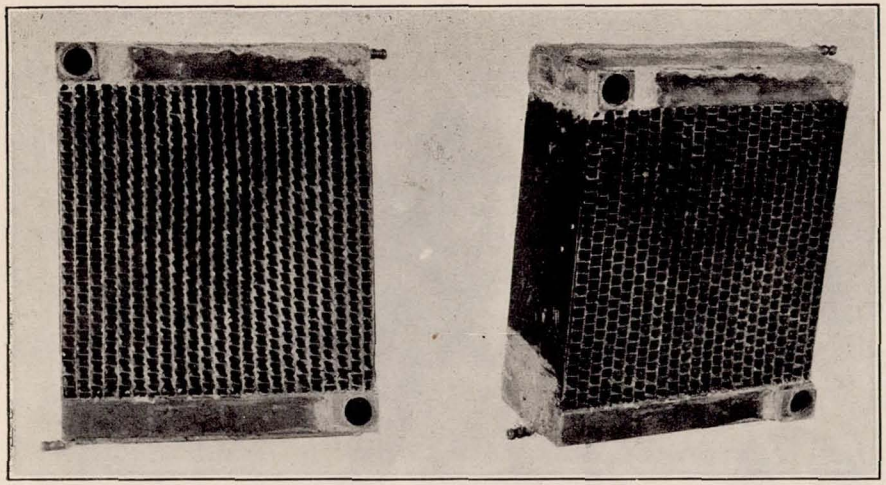


FIGURE 9.—The Modine Manufacturing Co. $1\frac{1}{2}$-inch square tube with spirals. Core $3\frac{1}{2}$ inches deep.

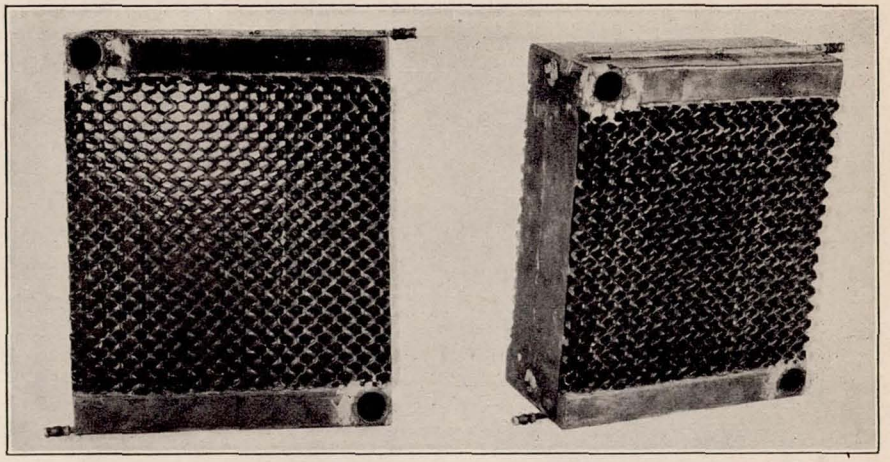


FIGURE 10.—The Sparks-Withington Co. $\frac{3}{8}$-inch elliptical tube. Core $3\frac{1}{2}$ inches deep.

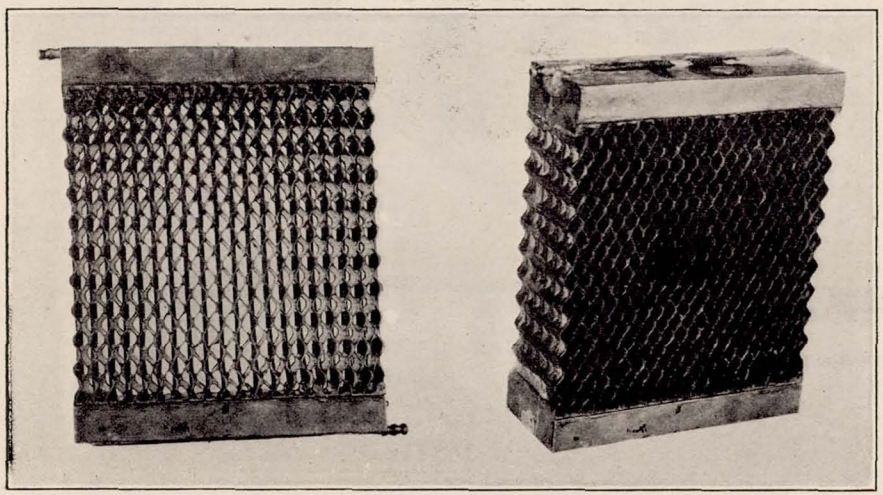


FIGURE 11.—The Hooven Sales Corporation. $\frac{5}{8}$-inch elliptical tube. Core $2\frac{5}{8}$ inches deep.

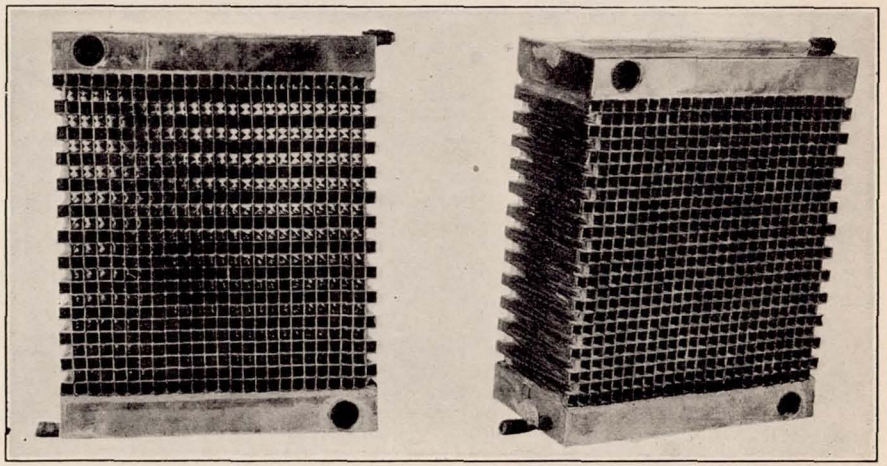


FIGURE 12.—The Western Mechanical Works. $\frac{5}{16}$-inch staggered square tube. Core 4 inches deep.

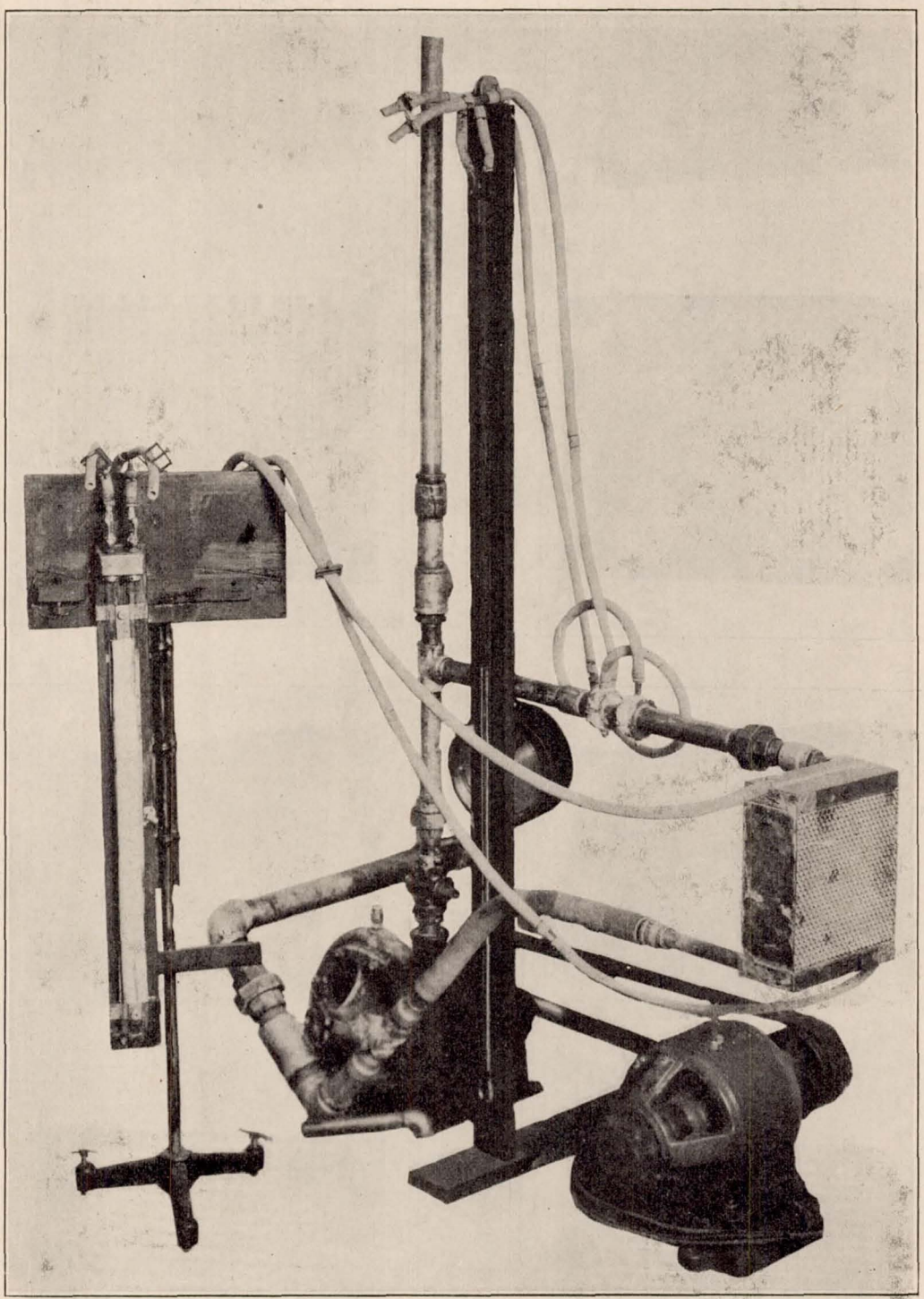
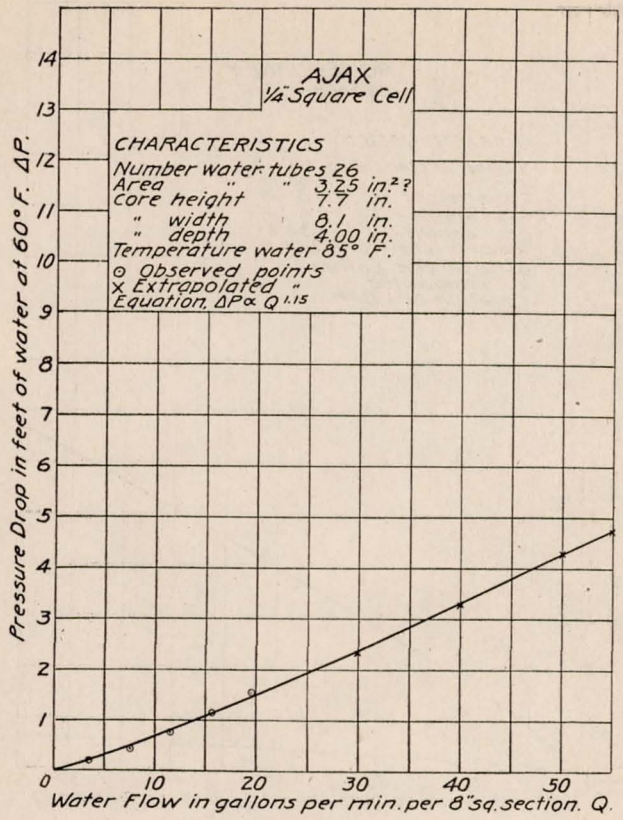
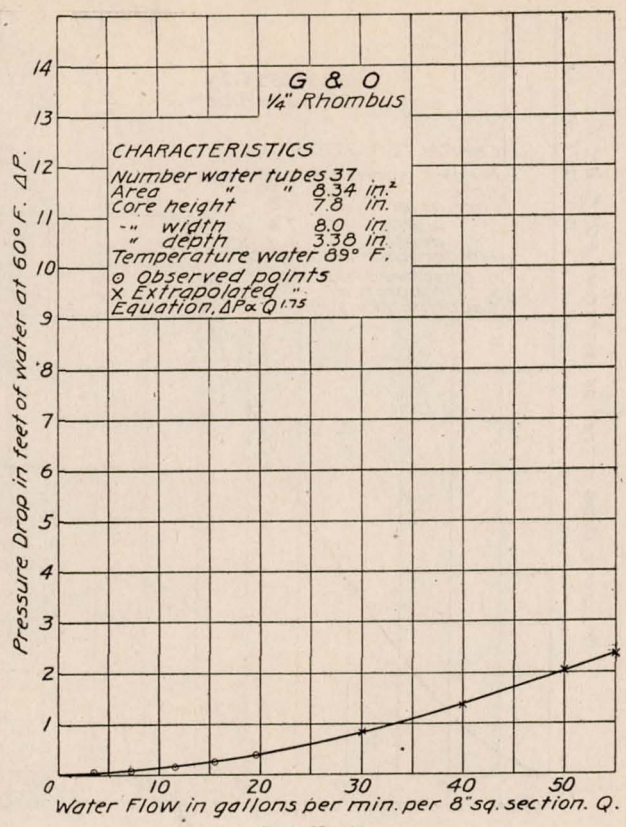


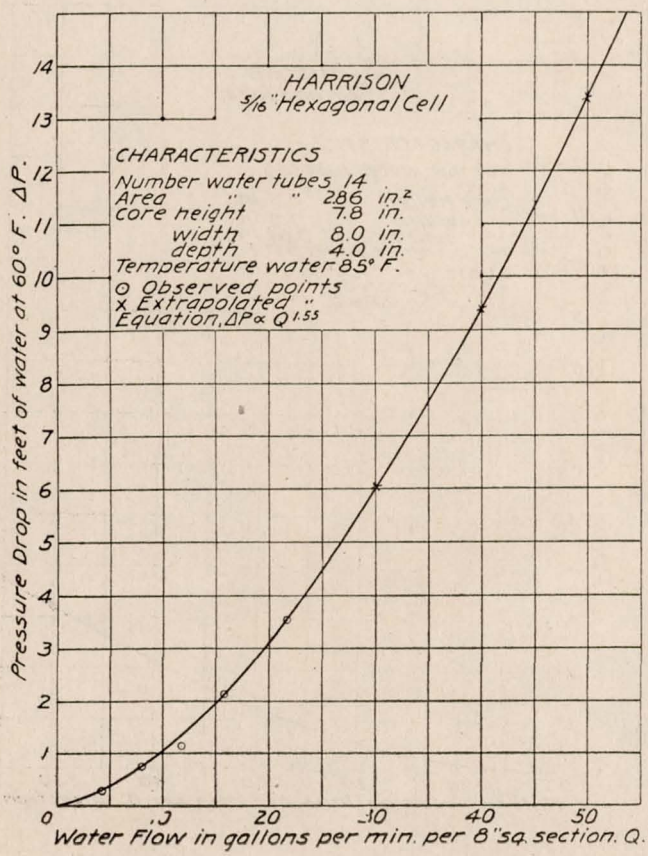
FIGURE 13.—Apparatus used to measure pressure necessary to produce water flow through radiator cores.



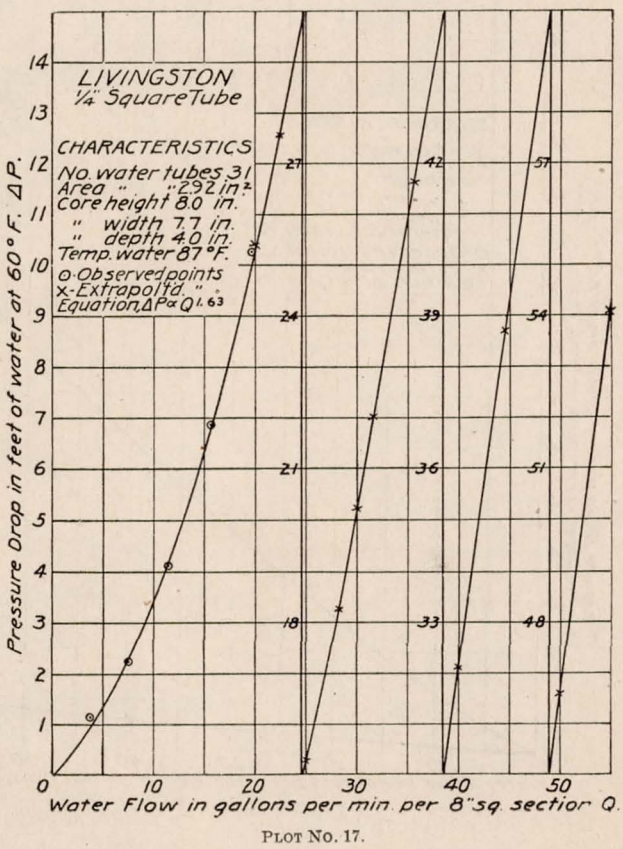
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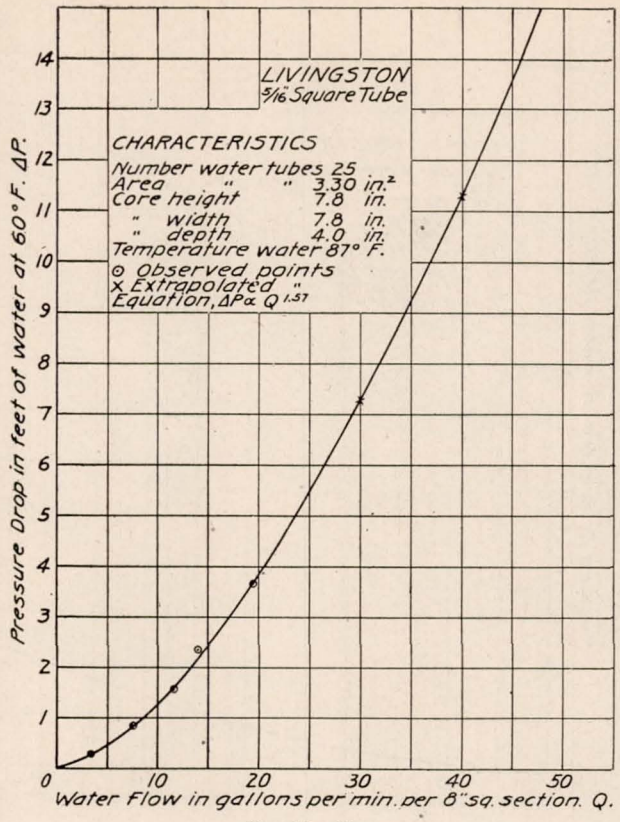
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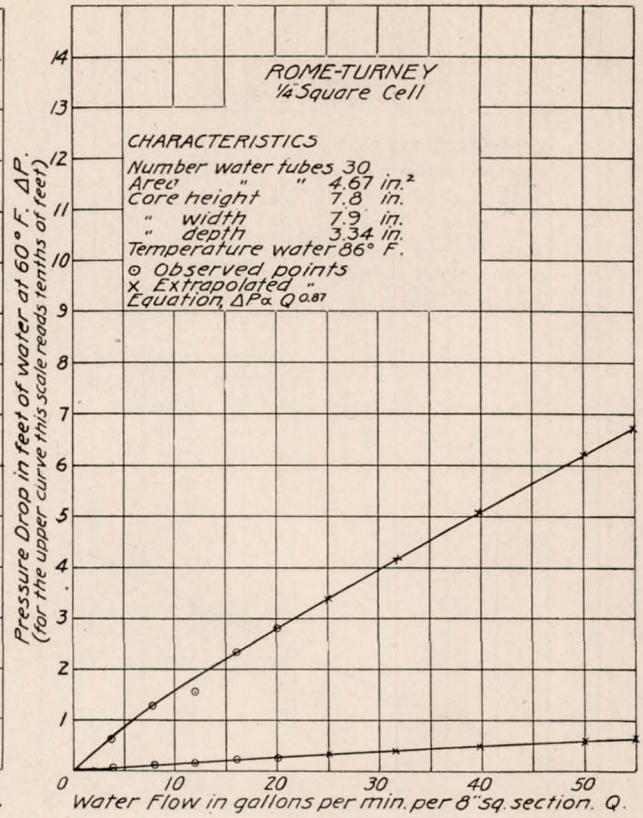
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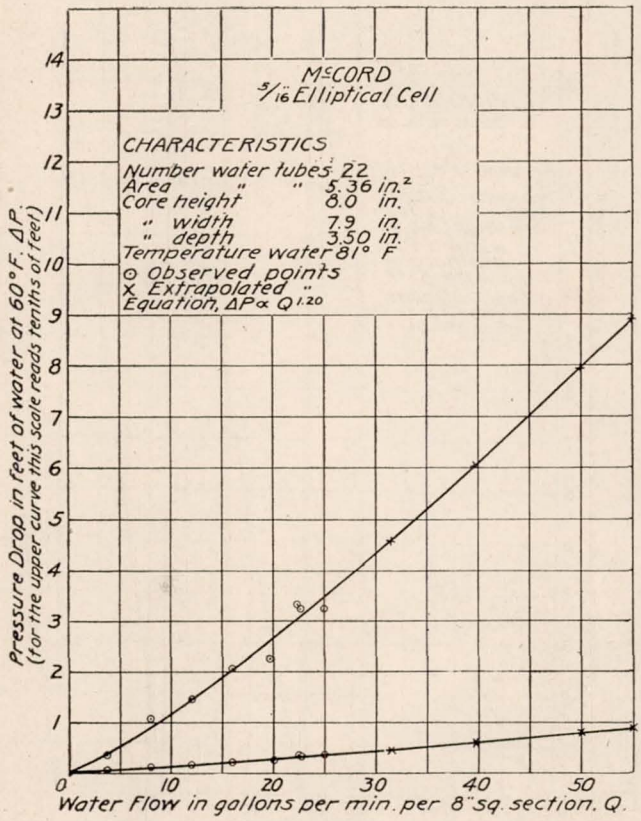
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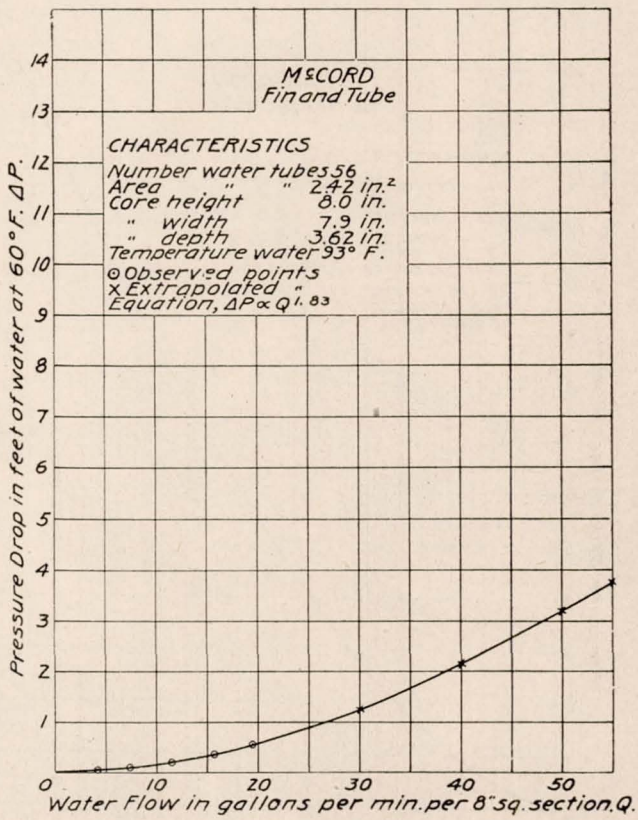
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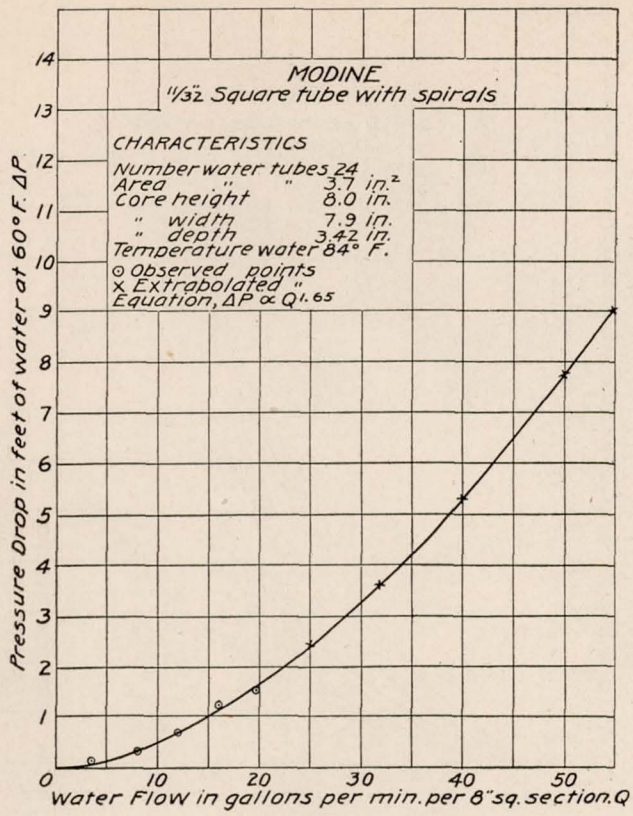
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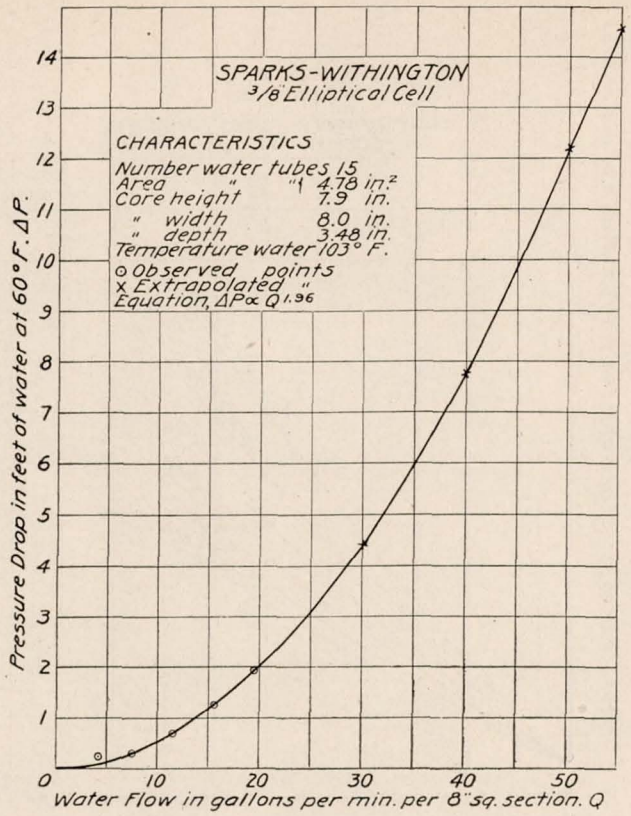
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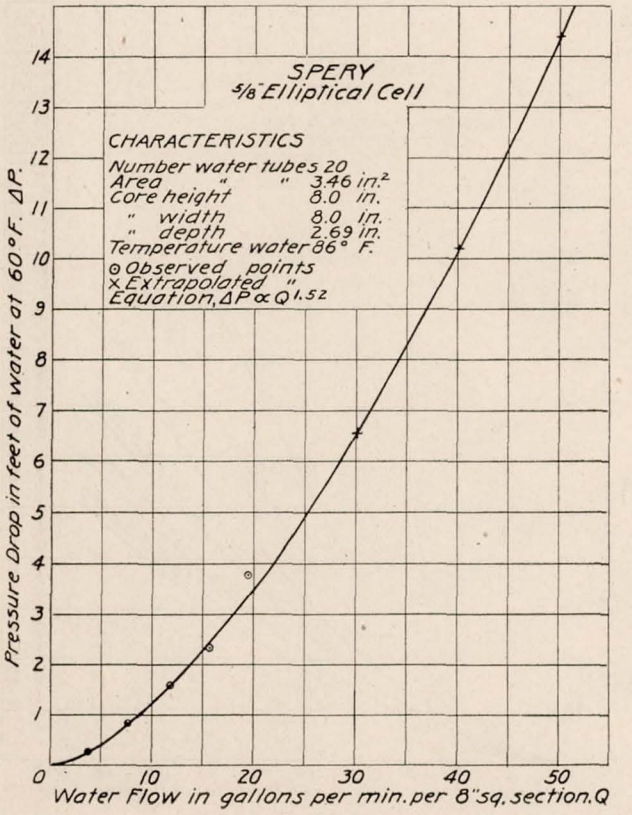
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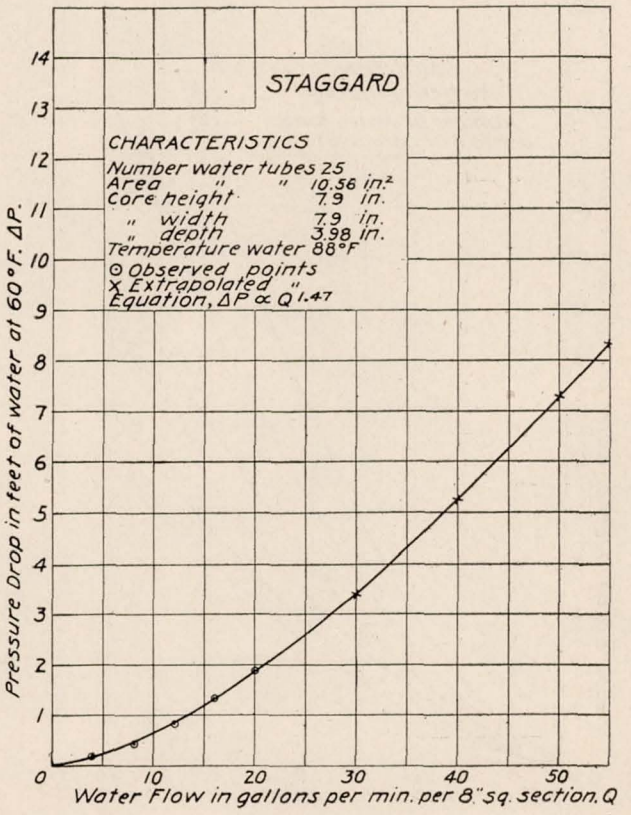
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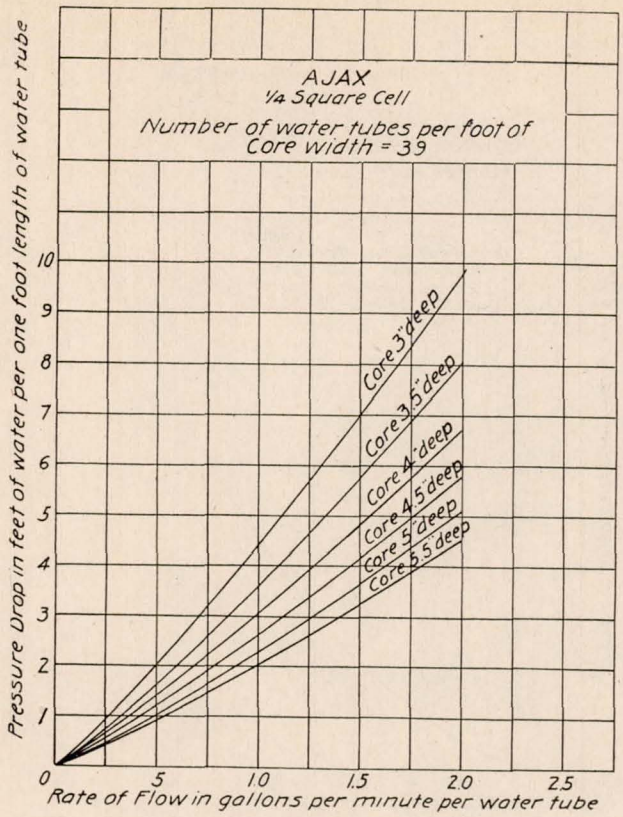
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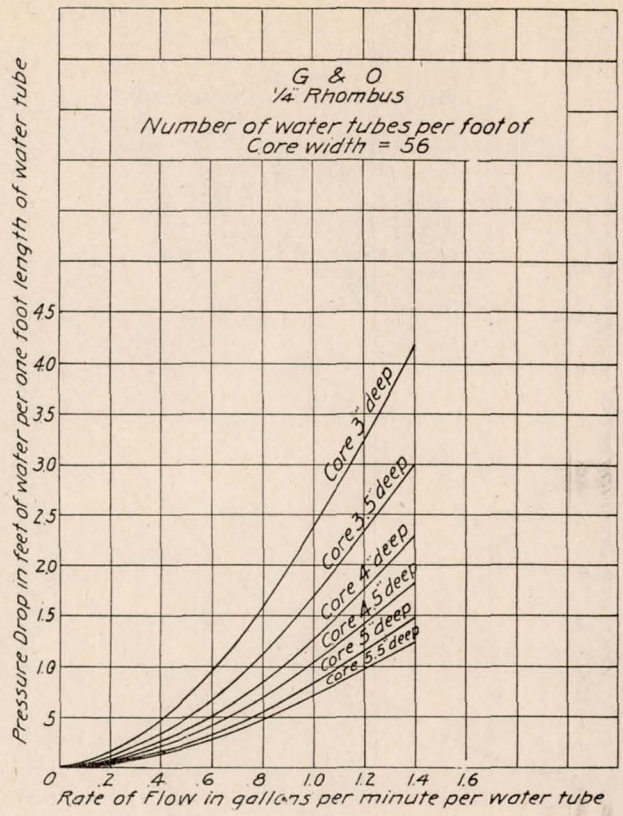
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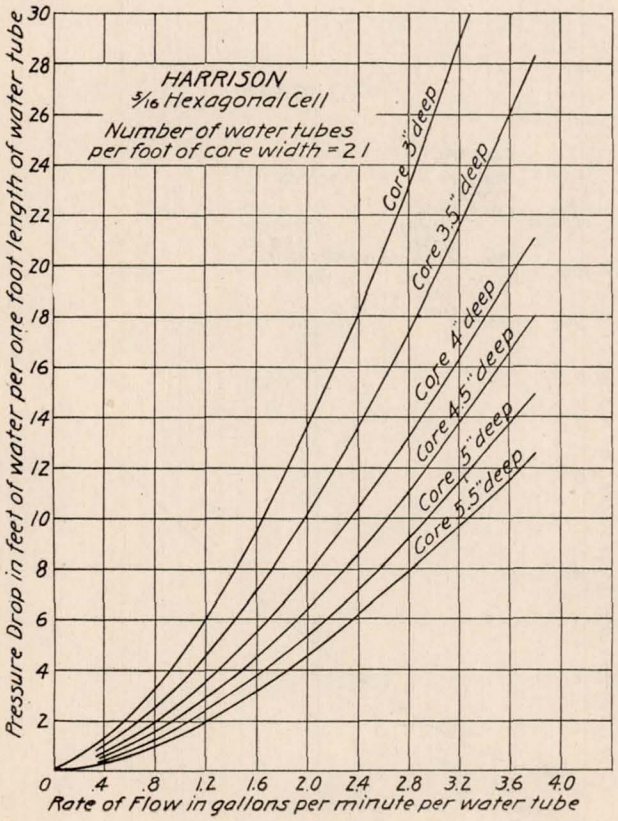
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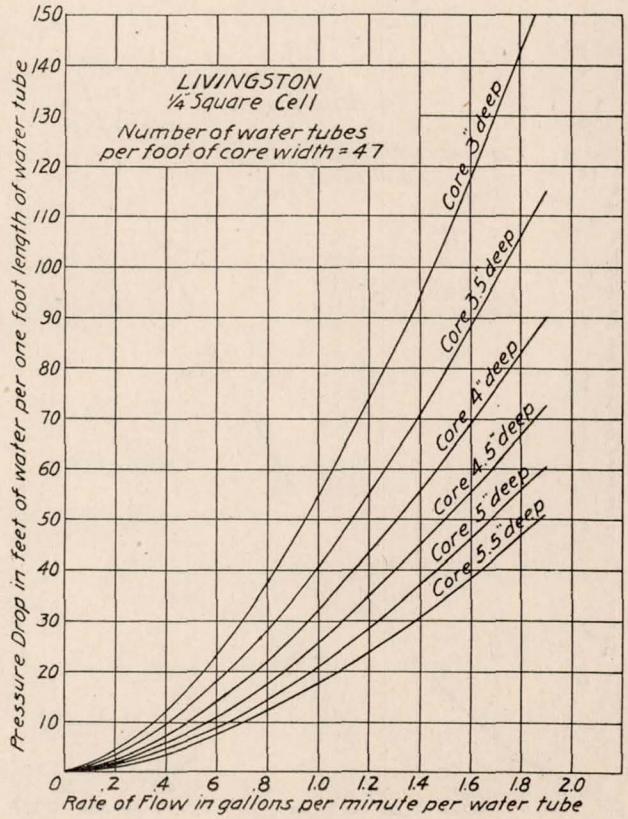
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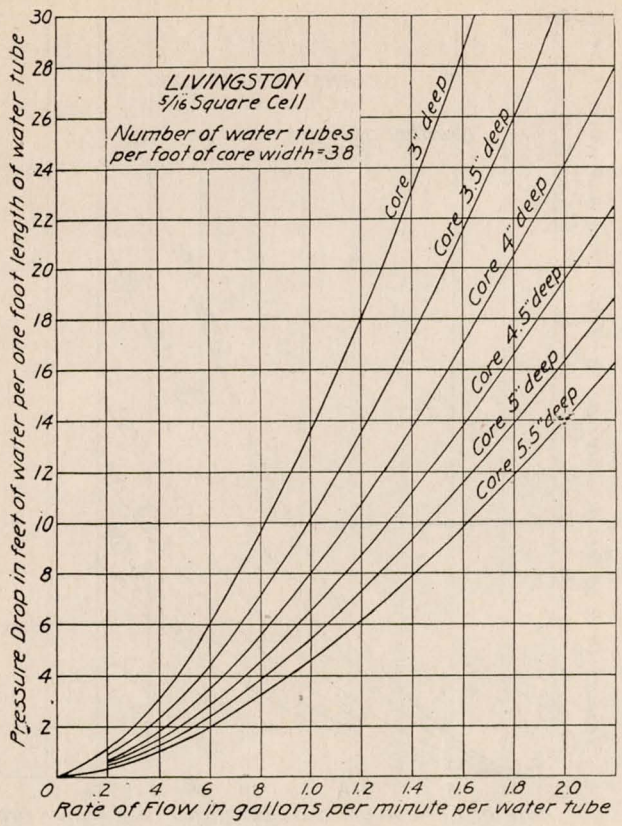
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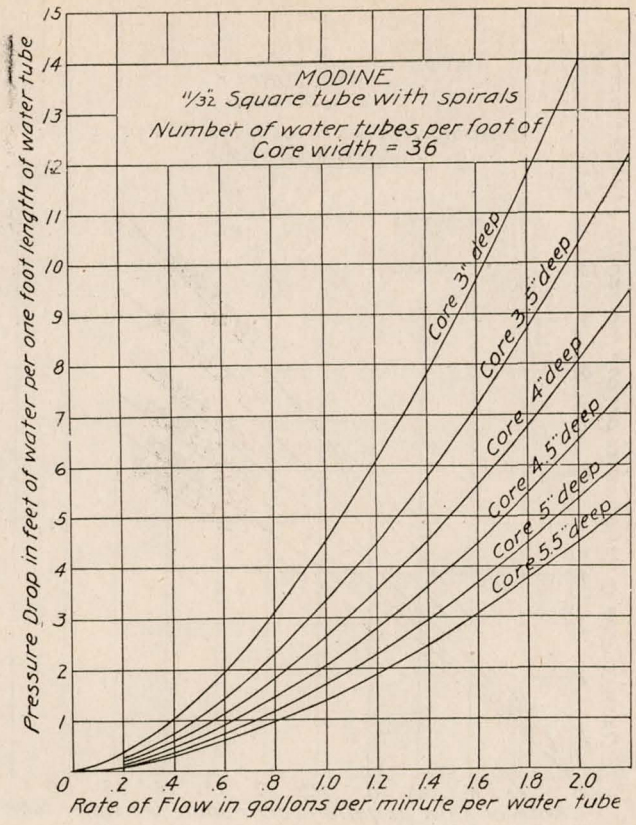
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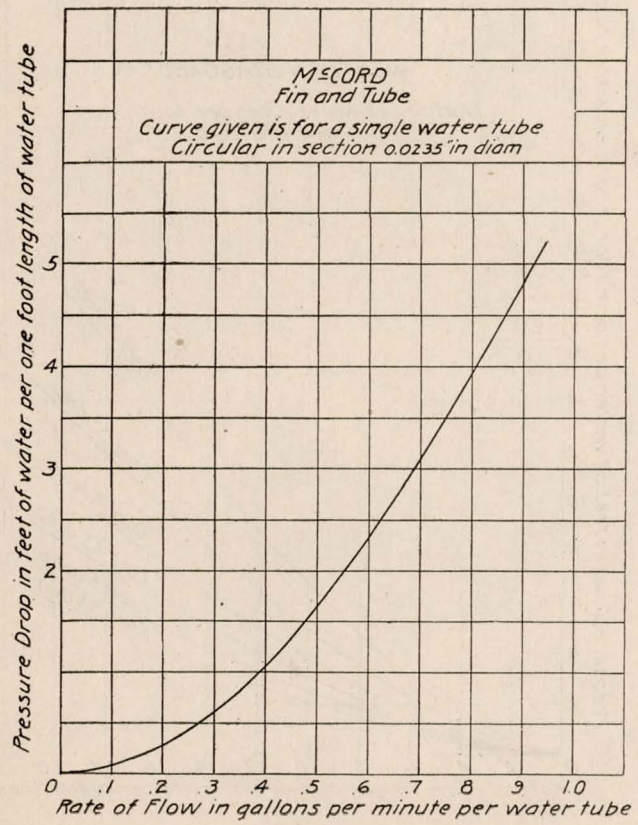
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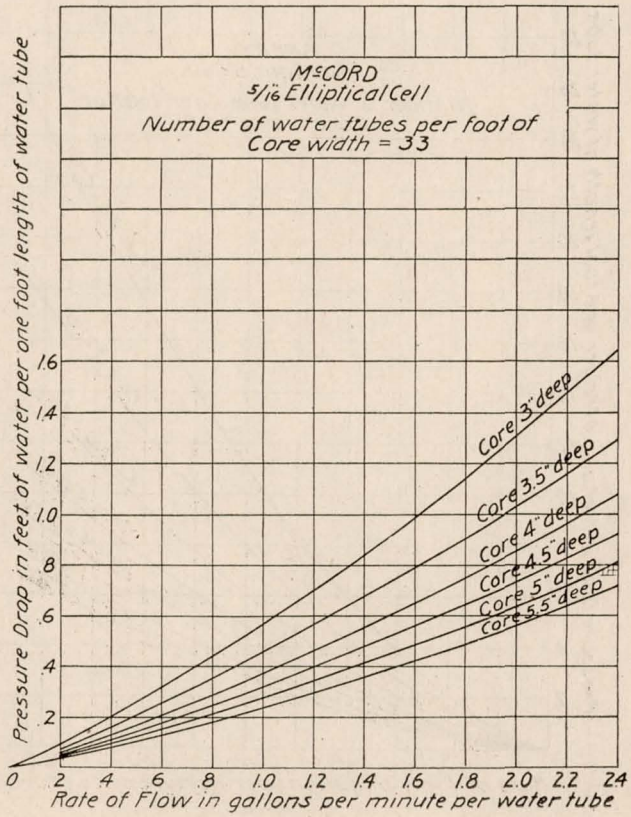
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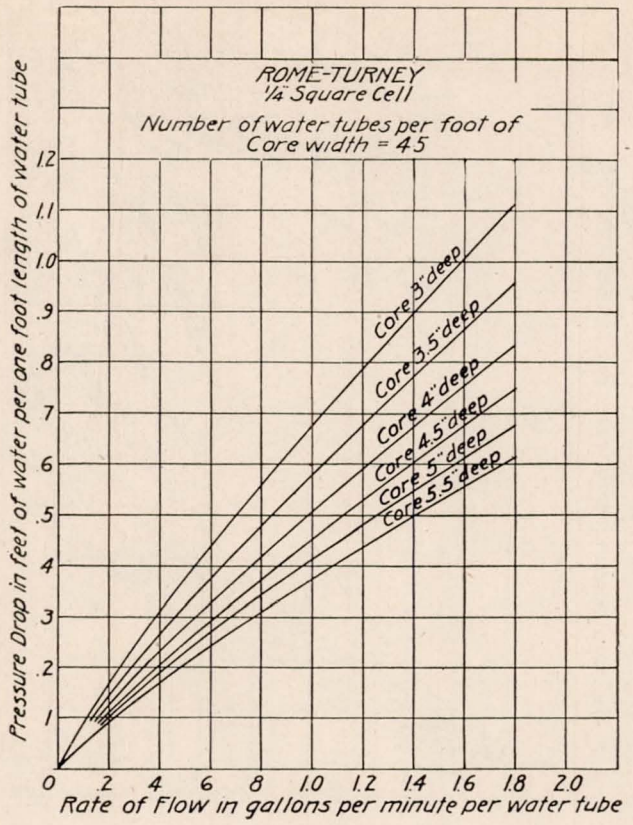
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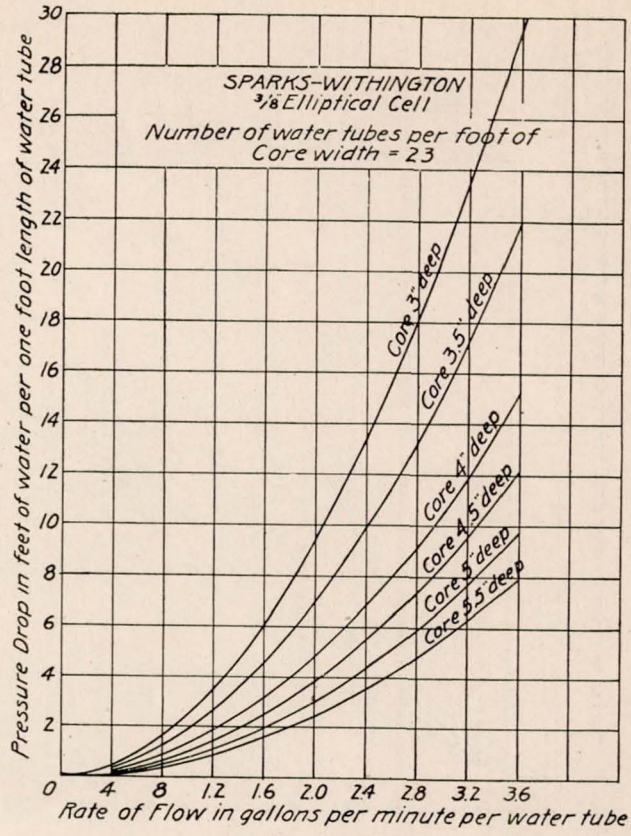
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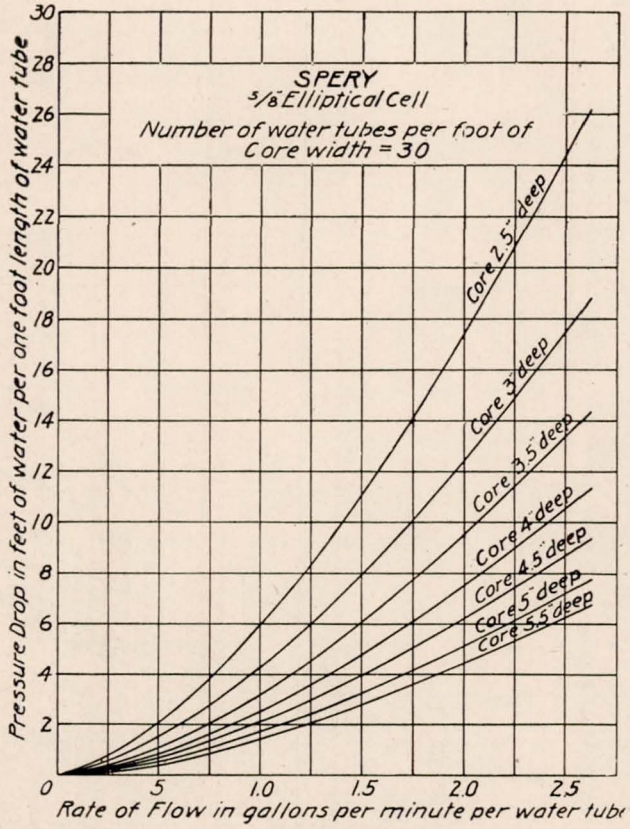
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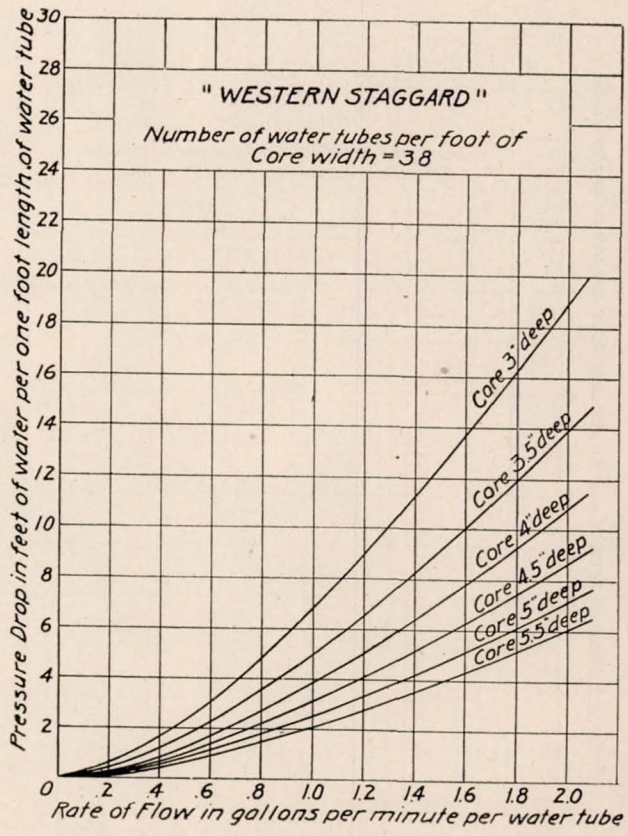
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PLOT No. 36.



PLOT No. 37.

REPORT No. 64.

EXPERIMENTAL RESEARCH ON AIR PROPELLERS, III.

By W. F. DURAND AND E. P. LESLEY

Leland Stanford Junior University, Stanford University, Calif.

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REPORT No. 64.

EXPERIMENTAL RESEARCH ON AIR PROPELLERS, III.

By W. F. DURAND and E. P. LESLEY.

SCOPE OF THE INVESTIGATION COVERED BY PRESENT TESTS.

The investigation described in this report was conducted for the National Advisory Committee for Aeronautics at Leland Stanford Junior University, Palo Alto, Calif.

The investigation on air propellers carried on during the two years 1917–18 and forming the subject of reports Nos. 14 and 30 [1] of the National Advisory Committee for Aeronautics covered the following general characteristics of form and design:

Four nominal pitch ratios, viz, 0.5, 0.7, 0.9, and 1.1.

Two forms of blade contour, (1) with approximately parallel sides and slightly rounded tip and (2) curved and tapering in accordance with the common saber form.

Two mean width ratios, viz, 15 per cent and 20 per cent of the radius of the propeller.

Two forms on the driving face, viz, plane and cambered or hollowed.

Two forms of distribution of geometrical pitch, (1) uniform and (2) increasing radially as determined by the assignment of a constant theoretical angle of attack.

In the study of the hollowed or cambered driving face, all combinations of characteristics otherwise with a degree of camber measured by one-third the thickness of the corresponding straight-face section were tested, while six with a degree of camber one-half the preceding were tried.

In the study of propellers with radially increasing pitch, this feature had not been extended to those of nominal pitch ratio 1.1.

In addition to propellers with combinations of characteristics as indicated above, a considerable number of tests were carried out, as recorded in report No. 30, covering a variety of forms of blade contour combined with one or more combinations of other characteristics.

In continuation of this general program of investigation, it seemed desirable to examine in particular the influence of the following characteristics:

(1) Nominal pitch ratio 1.3 combined with a certain number of the more common or standard forms and proportions.

(2) Driving face slightly rounded or convex.

(3) Change in the location of the maximum thickness ordinate of the blade section.

(4) Pushing forward the leading edge of the blade, thus giving a rounded convex surface on the leading side of the driving face.

(5) A series of values for the constant "angle of attack" in forming propellers with radially increasing pitch.

In accordance with these purposes tests have been carried out on some 28 propellers, figure 1, having characteristics as follows

Four propellers of nominal pitch ratio 1.3, uniform pitch, straight face, and with four combinations of form of blade and area as shown in Table I.

Five propellers of nominal pitch ratios 0.5, 0.7, 0.9, 1.1, and 1.3, all of uniform pitch, one area and one blade form, and with the driving face made slightly convex by adding a crown of one-sixth the normal thickness of the corresponding straight-face sections, as shown in Table I and in sections, figure 2.

[1] See Third Annual Report, 1917, and Fourth Annual Report, 1918.

TABLE I.—*Characteristics of model propellers.*

No.	Diameter.	Nominal pitch ratio.	Nominal pitch.	Mean blade width.	Form or contour No.	Section No.	Dynamic pitch ratio.	Dynamic pitch.
	Inches.		*Inches.*					*Inches.*
111	36	1.3	46.8	0.15*r*	F_1	S_1	1.637	58.97
112	36	1.3	46.8	.20*r*	F_1	S_1	1.518	54.64
113	36	1.3	46.8	.15*r*	F_2	S_1	1.623	58.41
114	36	1.3	46.8	.20*r*	F_2	S_1	1.52	54.72
115	36	.5	18.0	.15*r*	F_2	S_4	.735	26.47
116	36	.7	25.2	.15*r*	F_2	S_4	.934	33.62
117	36	.9	32.4	.15*r*	F_2	S_4	1.139	41.00
118	36	1.1	39.6	.15*r*	F_2	S_4	1.371	49.37
119	36	1.3	46.8	.15*r*	F_2	S_4	1.55	55.8
120	36	.7	25.2	.15*r*	F_2	S_5	.865	31.14
121	36	.7	25.2	.15*r*	F_2	S_6	.903	32.5
122	36	.7	25.2	.15*r*	F_2	S_7	.961	34.6
123	36	.7	25.2	.15*r*	F_2	S_8	.997	35.9
124	36	.7	25.2	.15*r*	F_2	S_9	.965	34.74
125	36	.7	25.2	.15*r*	F_2	S_{10}	.991	35.68
126	36	.7	25.2	.15*r*	F_2	S_{11}	1.013	36.47
127	36	.5	12.32–21.29	.15*r*	F_2	S_1	.675	24.30
128	36	.5	9.16–23.00	.15*r*	F_2	S_1	.656	23.62
129	36	.7	20.1 –28.45	.15*r*	F_2	S_1	.912	32.83
130	36	.7	16.31–30.13	.15*r*	F_2	S_1	.885	31.87
131	36	.9	28.29–35.57	.15*r*	F_2	S_1	1.126	40.55
132	36	.9	25.24–37.23	.15*r*	F_2	S_1	1.099	39.57
133	36	1.1	33.5 –41.1	.15*r*	F_2	S_1	1.394	50.20
134	36	1.1	36.71–42.6	.15*r*	F_2	S_1	1.377	49.60
135	36	1.1	34.09–44.2	.15*r*	F_2	S_1	1.351	48.65
136	36	1.3	45.6 –48.18	.15*r*	F_2	S_1	1.67	60.13
137	36	1.3	45.52–49.6	.15*r*	F_2	S_1	1.637	58.97
138	36	1.3	43.55–51.2	.15*r*	F_2	S_1	1.606	57.82

Four propellers of nominal pitch ratio 0.7, uniform pitch, one blade form and area, and four locations of the maximum thickness ordinate of the blade section, as shown in Table I and in sections, figures 3, 4, 5, and 6.

Three propellers of nominal pitch ratio 0.7, uniform pitch, one blade form and area, and with three degrees of deformation of the leading edge by pushing forward, as shown in Table I and in sections, figures 7, 8, and 9.

Twelve propellers distributed over the five pitch ratios 0.5, 0.7, 0.9, 1.1, 1.3, all with one blade form and area and with radially expanding pitch derived from the assumption of varying theoretical "angles of attack," as shown in Table I.

The four propellers 111, 112, 113, and 114, of nominal pitch ratio 1.3, fall in as the last members of four series formed by the propellers having corresponding combinations of form and area and with the other pitch ratios as tested in previous years.

The five propellers 115, 116, 117, 118, and 119, with the slightly rounded driving face, give a series representing a single blade form and area carried through the five nominal pitch ratios as shown in Table I.

The four propellers 120, 121, 122, and 123, with four different positions of the maximum thickness ordinate of the blade section, all of one pitch ratio, blade form and area, form with the corresponding propeller (No. 7) tested in 1917,[1] a series of five propellers with five positions of the maximum thickness ordinate, viz, 33 per cent, from the leading edge for No. 7 (which closely represents standard practice) and positions on either side as follows:

No. 120, maximum thickness of section 0.17 per cent of width from leading edge; No. 121, 25 per cent; No. 122, 41 per cent; No. 123, 49 per cent. The combination of characteristics otherwise (pitch ratio, form and area) selected for this series was intended to represent an average or typical case.

The three propellers, 124, 125, and 126, with leading edge pushed forward, give with No. 7 a single series with three successive amounts of such deformation, all of a single-type combination otherwise. In No. 7 the driving face is straight; in Nos. 124, 125, and 126 the leading edges are moved forward 25 per cent, 50 per cent, and 75 per cent of the maximum thickness of section, respectively.

The 12 propellers, 127 to 138, show in Table I a single value for nominal pitch ratio and two values for nominal pitch. The former is the pitch ratio of the driving face at 13-inch radius

[1] See Third Annual Report, 1917.

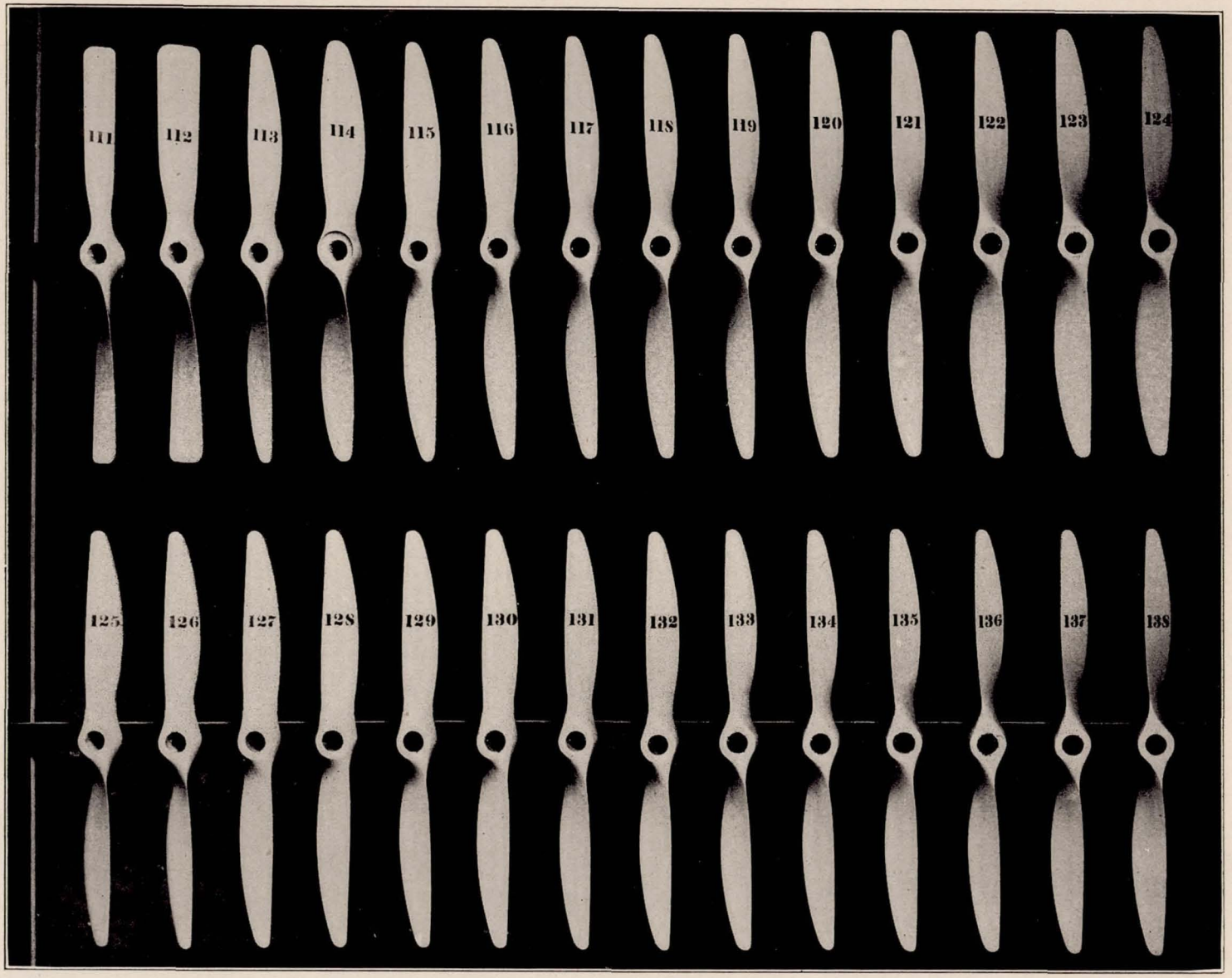


FIG. 1.—MODEL PROPELLERS.

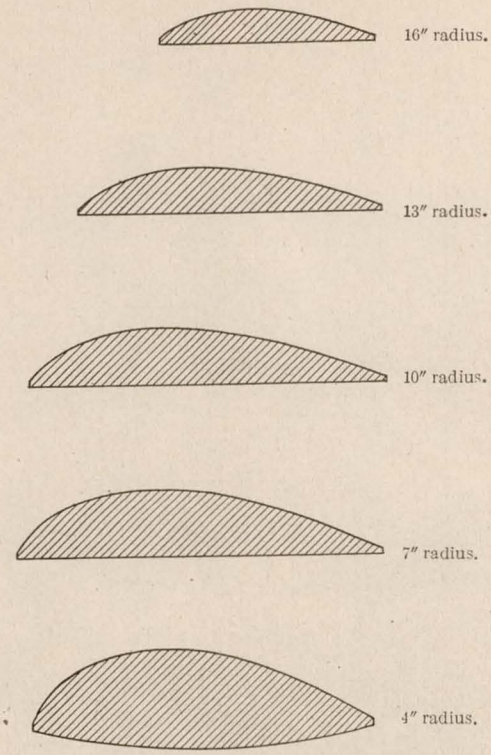


FIG. 2—Sec. 4. Prop. Nos. 115, 116, 117, 118, 119.

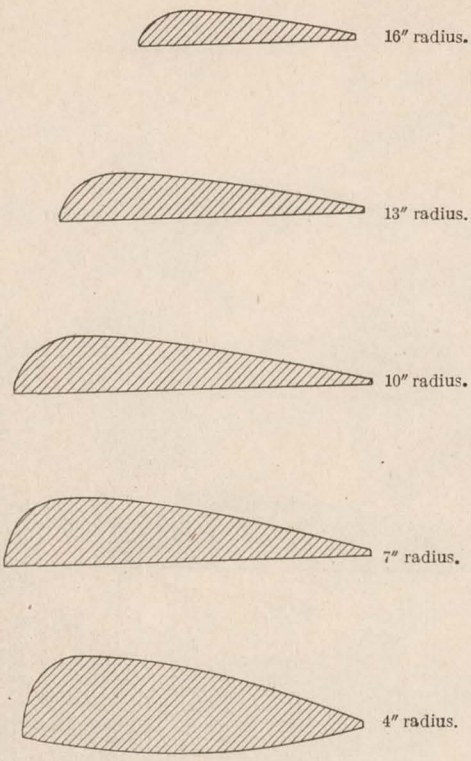
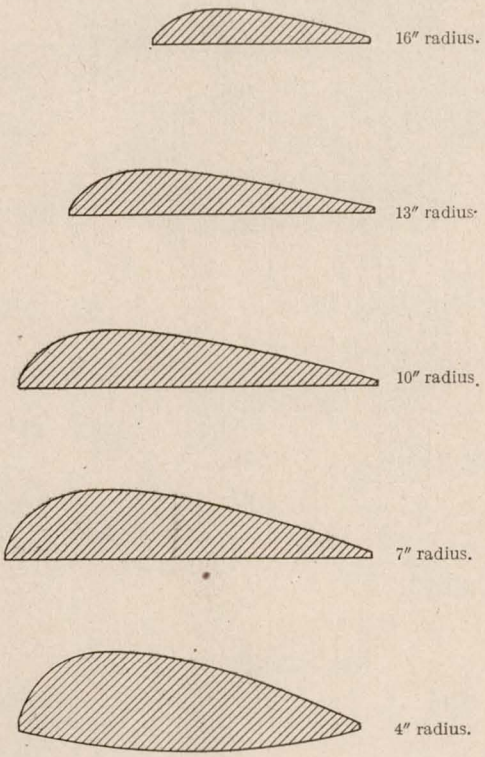


FIG. 3—Sec. 5. Prop. No. 120.



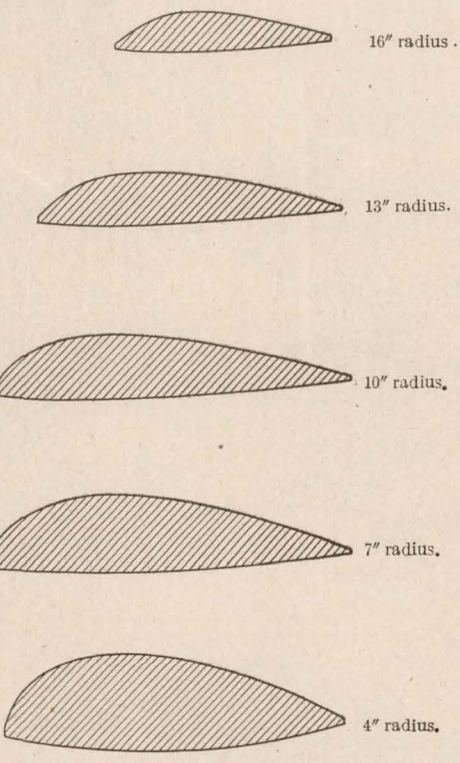


FIG. 5—Sec. 7. Prop. No. 122.

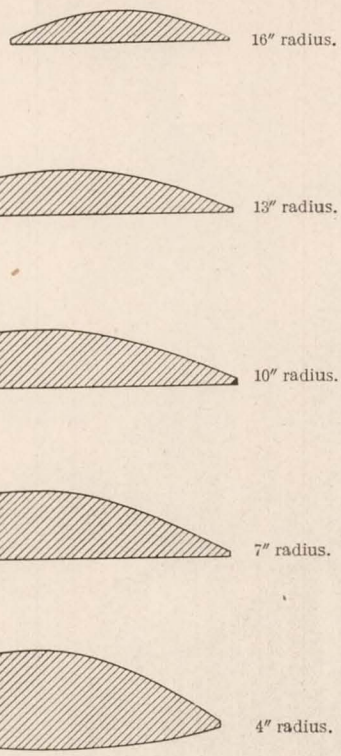


FIG. 6—Sec. 8. Prop. No. 123.

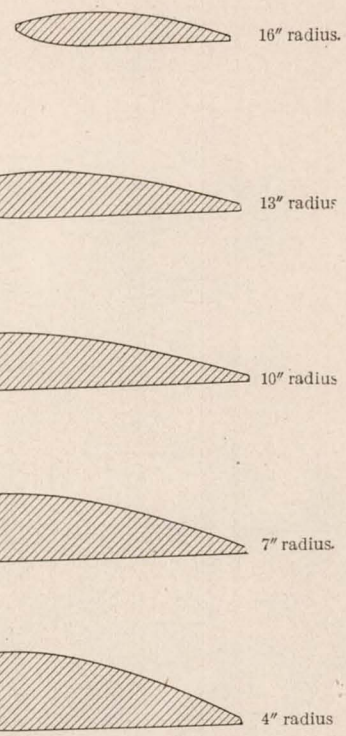


FIG. 7—Sec. 9. Prop. No. 124.

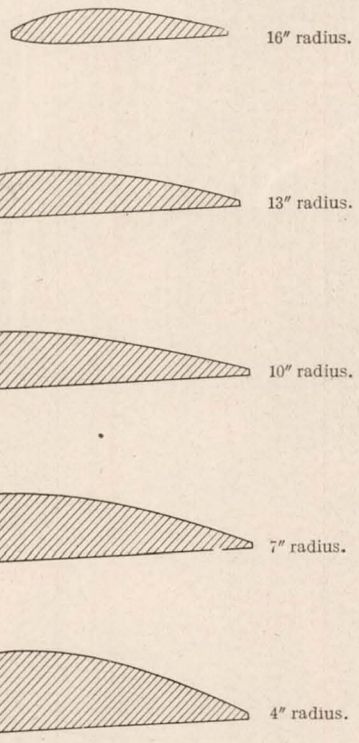


FIG. 8—Sec. 10. Prop. No. 125.

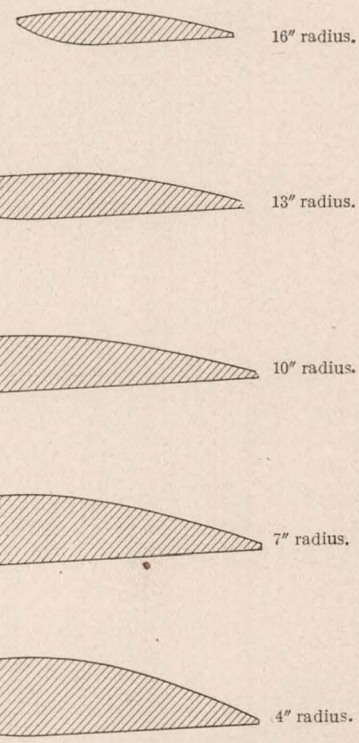


FIG. 9—Sec. 11. Prop. No. 126.

and the latter are the pitches of the driving face at the 4 and 18 inch radii, respectively. These propellers were given a radially increasing pitch according to the Drzewiecki method. For all blades showing the same value of nominal pitch ratio the pitch of the driving face at the 13-inch radius equals the diameter multiplied by the value of pitch ratio given. The following table shows the assumed constant "angle of attack" which gives rise to the variation in nominal pitch tabulated:

TABLE II.—*Assumed constant "angle of attack."*

Propeller No.	Nominal pitch ratio.	Assumed constant "angle of attack."
		Degrees.
127	0.5	6
128	.5	9
129	.7	6
130	.7	9
131	.9	6
132	.9	9
133	1.1	3
134	1.1	6
135	1.1	9
136	1.3	3
137	1.3	6
138	1.3	9

The contour, area, and section of propellers 127 to 138 are the same as for 3, 7, 11, 15, 19, and 23 of the 1917 report; 82 of the 1918 report; and 113 of the present investigation. The 20 may then be arranged in the following five series:

	Nos.
0.5 nominal pitch ratio	11, 23, 127, 128
.7 nominal pitch ratio	7, 19, 129, 130
.9 nominal pitch ratio	3, 15, 131, 132
1.1 nominal pitch ratio	82, 133, 134, 135
1.3 nominal pitch ratio	113, 136, 137, 138

The first of each series has a uniform pitch; the second has a radially expanding pitch produced by the assumption of a 3° "angle of attack"; the third one for a 6° "angle of attack"; the fourth one for a 9° "angle of attack."

All propellers in one series have the same geometrical pitch at the 13-inch radius. It should be noted that the effect of an assumed constant "angle of attack" varies inversely with the nominal pitch ratio. For instance, with propeller No. 127 (6°, 0.5 pitch ratio) the pitch changes from 12.32 to 21.29 inches, a variation of about 43 per cent of the maximum, while for propeller 137 (6°, 1.3 pitch ratio) the change is from 45.52 to 49.60 inches, a variation of less than 9 per cent of the maximum.

CONSTRUCTION OF MODELS.

The model propellers were carved from single sticks of well-seasoned Pacific coast sugar pine (*Pinus Lambertiana*) in the manner previously described. A departure was made from previous practice in the method of finish. After carving and sandpapering, the smooth bare wood was given one coat of orange shellac. This was rubbed with fine sandpaper and the surface given three to four coats of flat gray paint, put on very thin with a camel's-hair brush. Each coat was thoroughly dried and rubbed smooth, small surface defects being corrected with a filler. The propellers were then given two coats of rubbing varnish, the first being rubbed to surface with pumice and water and the second left glossy. The resultant finish is smooth, thin, and hard. For photographing, a single coat of flat gray was applied after tests were completed.

AERODYNAMIC LABORATORY.

Tests on the present series of model propellers were conducted in the aerodynamic laboratory at Stanford University, California, during the month of September, 1919. The wind tunnel is of similar form and proportions to that previously described,[1] but considerably larger,

[1] See Third Annual Report, 1917.

having a throat diameter of 7.5 feet. It is of somewhat more substantial construction, being solidly framed, and planked with $\frac{5}{8}$-inch thick tongue-and-groove flooring.

The wind fan is 15 feet diameter, with eight blades of 12-foot pitch. It is driven by a 100-horsepower, 220-volt, variable-speed, direct-current motor, with which, at 25 per cent overload, a wind velocity of 80 miles per hour may be realized.

TESTS.

The tests were conducted in a similar manner to those described in the 1918 annual report. Somewhat greater wind velocities were used, it being the practice to start the test with a wind velocity of about 45 miles per hour. After the safe limit of thrust (about 50 pounds) or the power limit of the driving motor (12 horsepower) was reached with this velocity, observations were made at higher slips by reducing the wind velocity until the useful range of slip had been covered.

The thrust-torque dynamometer and other devices used in 1917 and 1918 were employed in these present tests. The thrust balance, torque springs, and wind-speed meter were subjected to frequent careful calibrations as previously.

REDUCTION OF DATA.

The observations of thrust, torque, revolutions, velocity, and density were combined and reduced to the coefficients

$$\frac{V}{ND}.$$

$$T_c=\frac{100\times\text{thrust}}{\triangle V^2D^2},$$

$$\rho=\text{efficiency},$$

$$Q_c=\frac{1000\times\text{torque}}{\triangle V^2D^3},$$

$$\frac{P_u}{\triangle N^3D^5}=\frac{T_c}{100}\left(\frac{V}{ND}\right)^3,$$

and $$\frac{P_e}{\triangle N^3D^5}=\frac{Q_c}{1000}\left(\frac{V}{ND}\right)^2\times 2\pi.$$

Coefficients T_c, Q_c, and ρ were plotted on abscissæ of $\frac{V}{ND}$ for each observation and fair curves drawn through the points determined. The curves were checked for consistency at each 0.1 of $\frac{V}{ND}$.

Likewise log $\frac{P_u}{\triangle N^3D^5}$ and log $\frac{P_e}{\triangle N^3D^5}$ were plotted for each observation on log $\frac{V}{ND}$, and fair curves drawn and checked for consistency with T_c, Q_c, and ρ for each 0.1 of $\frac{V}{ND}$.

While English units were used in making observations, the results as presented are in metric units.

V = velocity meters per second.
N = revolutions per second.
D = diameter in meters.
T = thrust in kilograms.
Q = torque in kilogram meters.
$\triangle$ = density in kilograms per cubic meter.
P_u = useful work in kilogram meters per second.
P_e = effective work in kilogram meters per second.

1 metric horsepower = 75 kilogram meters per second.

All the coefficients are thus the same as those used in the 1918 report. Coefficients T_c, Q_c, $\frac{P_u}{\triangle N^3 D^5}$, and $\frac{P_e}{\triangle N^3 D^5}$ of the 1917 report are comparable to those of this investigation when multiplied by 3.28.

The results are presented in the form of curves of T_c, Q_c, and ρ, plotted on $\frac{V}{ND}$ (Pls. I to XVI) and of log $\frac{P_e}{\triangle N^3 D^5}$ and log $\frac{P_u}{\triangle N^3 D^5}$ plotted on log $\frac{V}{ND}$ (Pls. XVII to XXIV). The use of these diagrams has been described.[1] About one-half the observations actually made are plotted on the curves of T_c and Q_c, it being thought desirable to avoid confusion of the diagrams by multiplicity of points. Those shown are typical.

DISCUSSION OF RESULTS.

THRUST.

THRUST IN RELATION TO PITCH RATIO.

The curves of T_c for propellers 111, 112, 113, and 114 compared with those for propellers with similar characteristics except pitch show that in general for a given value of $\frac{V}{ND}$ thrust increases with pitch ratio. At the lower values of $\frac{V}{ND}$, however (below 0.5), it appears that the increment of thrust is less than that of pitch ratio and that the limit of thrust is soon reached. This is shown most clearly by curves of $\frac{P_u}{\triangle N^3 D^5}$ on Plates XIX, XXIII, and XXIV.

THRUST IN RELATION TO BLADE SECTION.

(*a*) *Rounded face.*—The thrust of propellers 115, 116, 117, 118, and 119 for the same value of $\frac{V}{ND}$ is less than that for the same form, area, and nominal pitch, straight-face blades 11, 7, and 3 of the 1917 report, 82 of the 1918 report, and 113 of the present series. A part of this reduction of thrust may be accounted for by the smaller dynamic pitch.

(*b*) *Position of maximum ordinate.*—Propellers 120, 121, 7 of 1917, 122, and 123 show that for a given value of $\frac{V}{ND}$ the thrust increases with the movement of the maximum ordinate of section away from the leading edge, until about 33 per cent of the width is reached. Beyond this there appears to be little change in thrust, No. 122 showing slightly less than No. 7 and No. 123 nearly the same. The variation in thrust is perhaps not greater than would be expected from the variation in dynamic pitch.

(*c*) *Leading one-third of face rounded by moving leading edge forward.*—Pushing the leading edge forward decreases thrust for a given value of $\frac{V}{ND}$ except at low slip, where 125 gives somewhat greater thrust than 124 and 126 greater than 125. The thrust of No. 7 (1917) is greater than any of above.

THRUST IN RELATION TO RADIALLY INCREASING PITCH.

For propellers 11, and 23 of 1917 and 127 and 128 of the present series, at a given value of $\frac{V}{ND}$, the thrust varies inversely with the "angle of attack." The variation is not greater than would be expected from the variation of dynamic pitch.

The same is true of series 7, 19, 129, and 130.

For series 3, 15, 131, 132; 82, 133, 134, 135; 113, 136, 137, 138; the differences are less marked. In some cases it is in one direction and in some in the other. This is accounted for by the fact that with the larger pitch ratios the variation of pitch is less than with the smaller pitch ratios for the same "angles of attack."

[1] Report 14, Third Annual Report 1917.

POWER.

POWER IN RELATION TO PITCH RATIOS.

As would be expected, the larger the pitch ratio, the greater the power absorbed at a given value of $\frac{V}{ND}$.

POWER IN RELATION TO BLADE SECTION.

(*a*) *Rounded face.*—The rounded-face blades 115, 116, 117, 118, and 119 absorb less power at a given value of $\frac{V}{ND}$ than the corresponding straight-face blades Nos. 11, 7, 3, 82, and 113.

(*b*) *Position of maximum ordinate of blade section.*—At a given value of $\frac{V}{ND}$ power increases as the maximum ordinate of the section is moved away from the leading edge until about 33 per cent of the width has been traversed. Beyond this point there is comparatively little difference in the models tested.

(*c*) *Leading one-third of face rounded by moving leading edge forward.*—Power absorbed for a given value of $\frac{V}{ND}$ increases as the leading edge of the propeller blade is pushed forward. An exception to this appears in propeller 126 where for values of $\frac{V}{ND}$ between 0.55 and 0.75 the power absorbed by No. 126 is slightly less than that for No. 125.

POWER IN RELATION TO RADIALLY INCREASING PITCH.

The two series 11, 23, 127, 128, and 7, 19, 129, 130 show the same general relations of power absorbed as of thrust developed; that is, power varying inversely with the "angle of attack." Also, as with thrust, the differences in the larger pitch ratios are small. In the case of series 113, 136, 137, 138 there is little difference between the torque curves. It is sometimes in one direction and sometimes in the other.

EFFICIENCY.

EFFICIENCY IN RELATION TO PITCH RATIO.

The 1.3 pitch ratio propellers show a larger range of efficiency and a slightly higher maximum than similar forms tested in 1918 (1.1 pitch ratio). There is a marked decrease in efficiency at the higher slips, some blades showing an efficiency curve which is slightly concave upward at the lower value of $\frac{V}{ND}$. This was not unexpected from tests on the variable pitch propeller No. 96 in 1918.

EFFICIENCY IN RELATION TO BLADE SECTION.

(*a*) *Rounded face.*—Propellers 115, 116, 117, 118, and 119 have practically the same efficiency curves as Nos. 11, 7, 3, 82, and 113 (straight face). Although the thrust developed is less for the former, the power absorbed is proportionally less, so that the efficiency is little affected. Having slightly less dynamic pitch, a slightly less maximum efficiency for the rounded-face series is to be expected. It appears, however, that the strength of blades may be considerably increased by slightly rounding the face, and with little or no corresponding loss in efficiency.

(*b*) Position of maximum ordinate.—Cross curves of efficiency for propellers 120, 121, 7 of 1917, 122, and 123 show highest efficiency for No. 7, whose maximum ordinate of section is one-third of the width from the leading edge. No. 121 appears superior to No. 120. There is little difference between Nos. 122 and 123, but both are distinctly less efficient than No. 7.

(*c*) *Leading one-third of face rounded by pushing leading edge forward.*—Pushing the leading edge forward increases the maximum efficiency attained but decreases the efficiency over the working range. The increase in maximum efficiency is not more than would be expected from the increase in dynamic pitch.

EFFICIENCY IN RELATION TO RADIALLY EXPANDING PITCH.

The five series of propellers, 11, 23, 127, 128; 7, 19, 129, 130; 3, 15, 131, 132; 82, 133, 134, 135; 113, 136, 137, 138, seem to indicate that no advantage in efficiency is to be gained from a radially expanding pitch produced by the method of design followed. Although these series show with increasing "angle of attack" slight increases in efficiency over the usual working range, there is an accompanying reduction in maximum efficiency, both of which results are to be expected from the decrease in dynamic pitch.

As with thrust and power, the differences for the small pitch ratios are more marked than those for the larger ones.

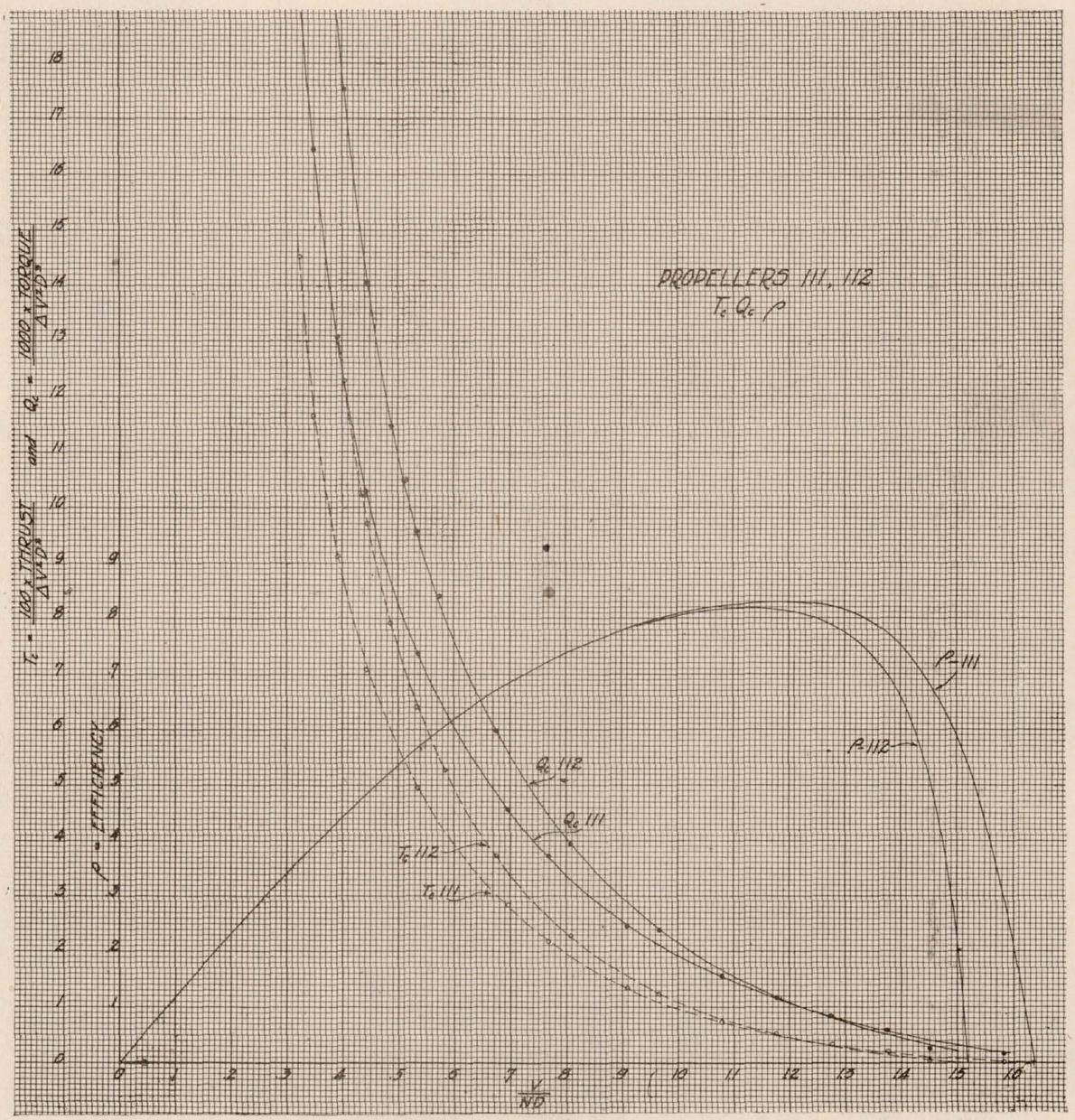

PROPELLERS 111, 112
T_c Q_c ρ
$T_c = \frac{100 \times \text{THRUST}}{\Delta V^2 D^2}$ and $Q_c = \frac{1000 \times \text{TORQUE}}{\Delta V^2 D^3}$
ρ = EFFICIENCY
ρ 111
ρ 112
Q_c 112
Q_c 111
T_c 112
T_c 111
$\frac{V}{ND}$

PLATE I.

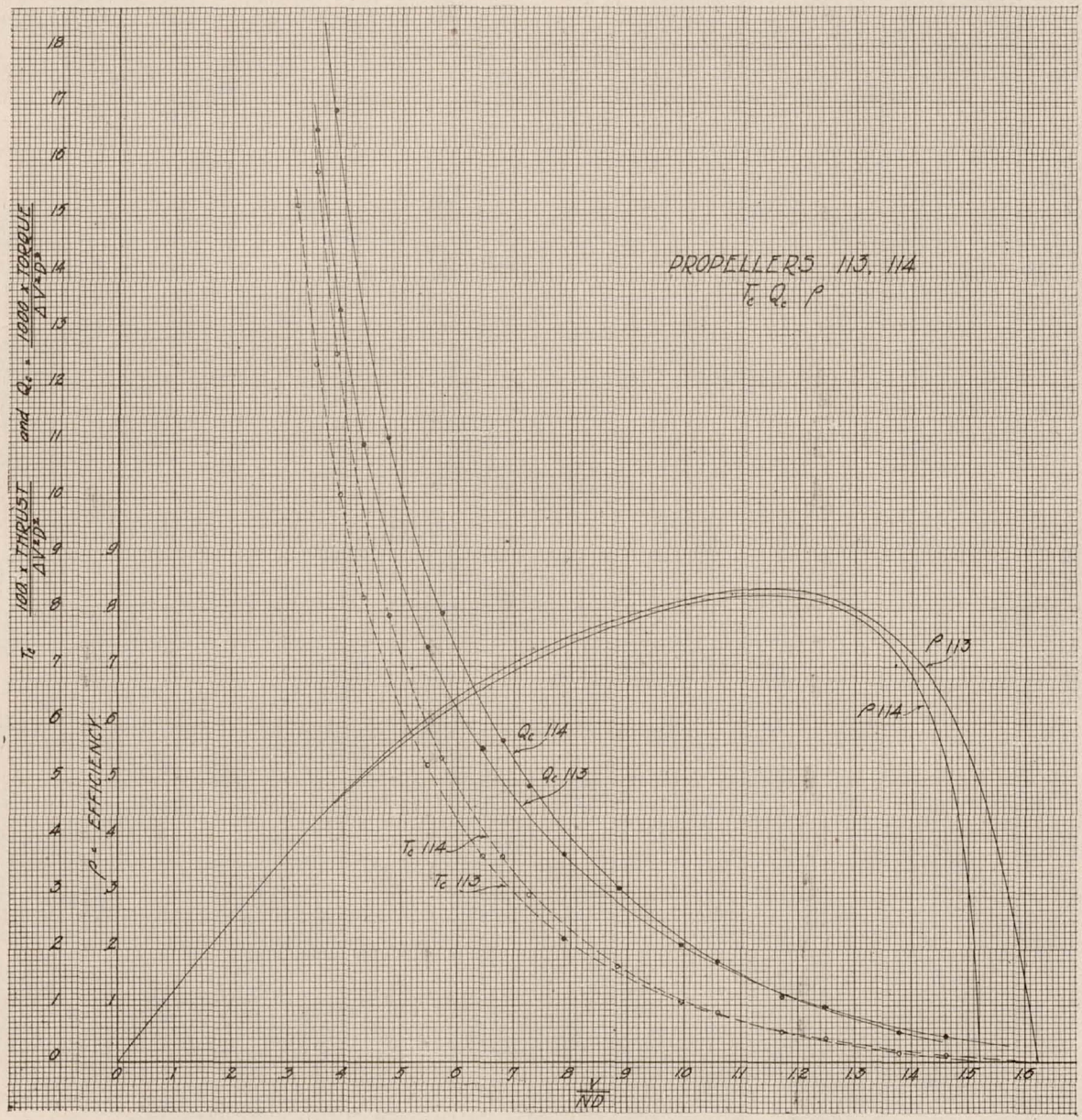

PROPELLERS 113, 114
T_c Q_c ρ
T_c 100 × THRUST / $\Delta V^2 D^2$ and Q_c = 1000 × TORQUE / $\Delta V^2 D^3$
ρ = EFFICIENCY
$\frac{V}{ND}$
P_{113}
P_{114}
Q_c 114
Q_c 113
T_c 114
T_c 113

PLATE II.

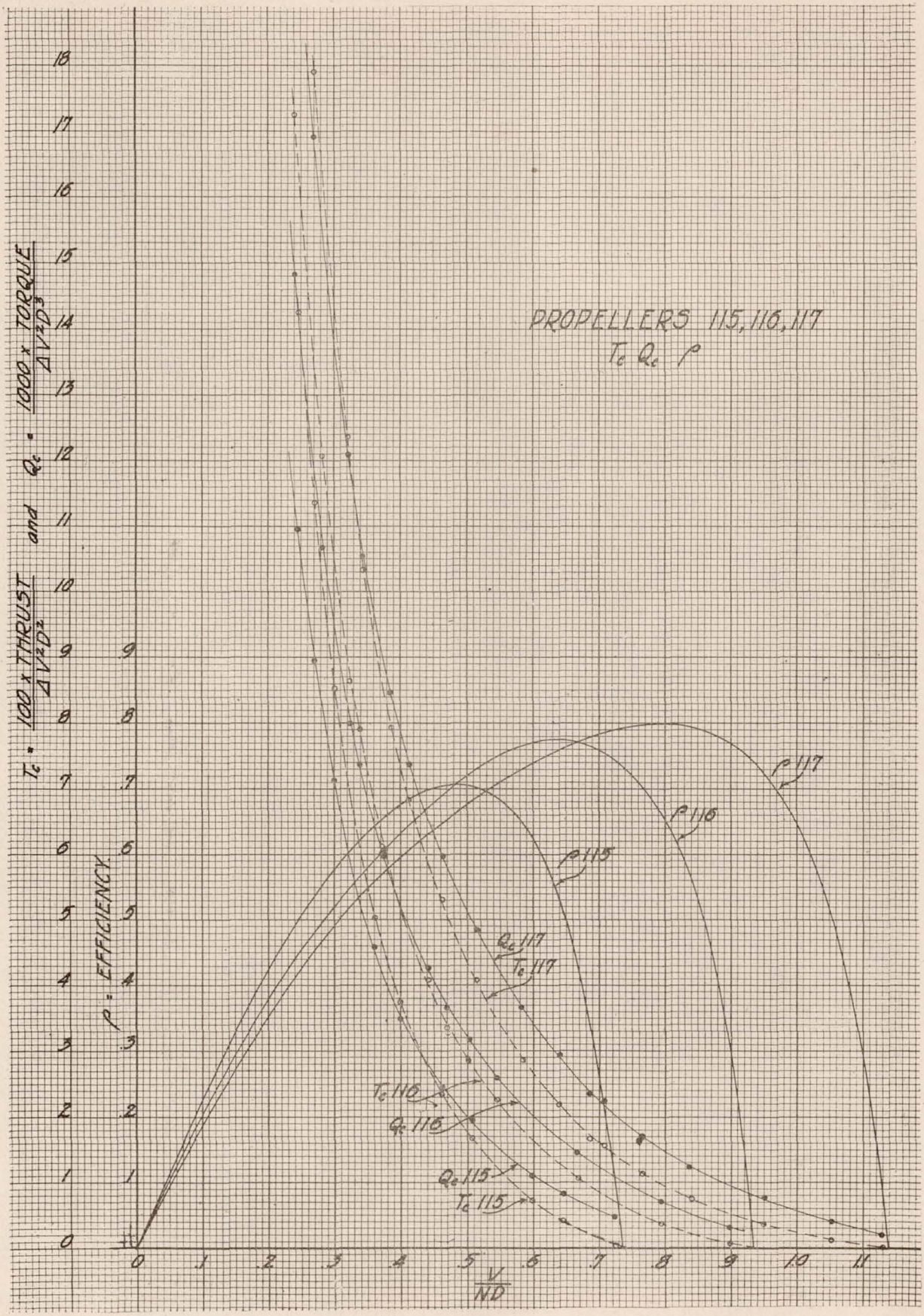

PROPELLERS 115, 116, 117
T_c Q_c ρ
$T_c = \frac{100 \times \text{THRUST}}{\Delta V^2 D^2}$ and $Q_c = \frac{1000 \times \text{TORQUE}}{\Delta V^2 D^3}$
ρ = EFFICIENCY.
$\frac{V}{ND}$
ρ 117
ρ 116
ρ 115
Q_c 117
T_c 117
T_c 116
Q_c 116
Q_c 115
T_c 115

PLATE III.

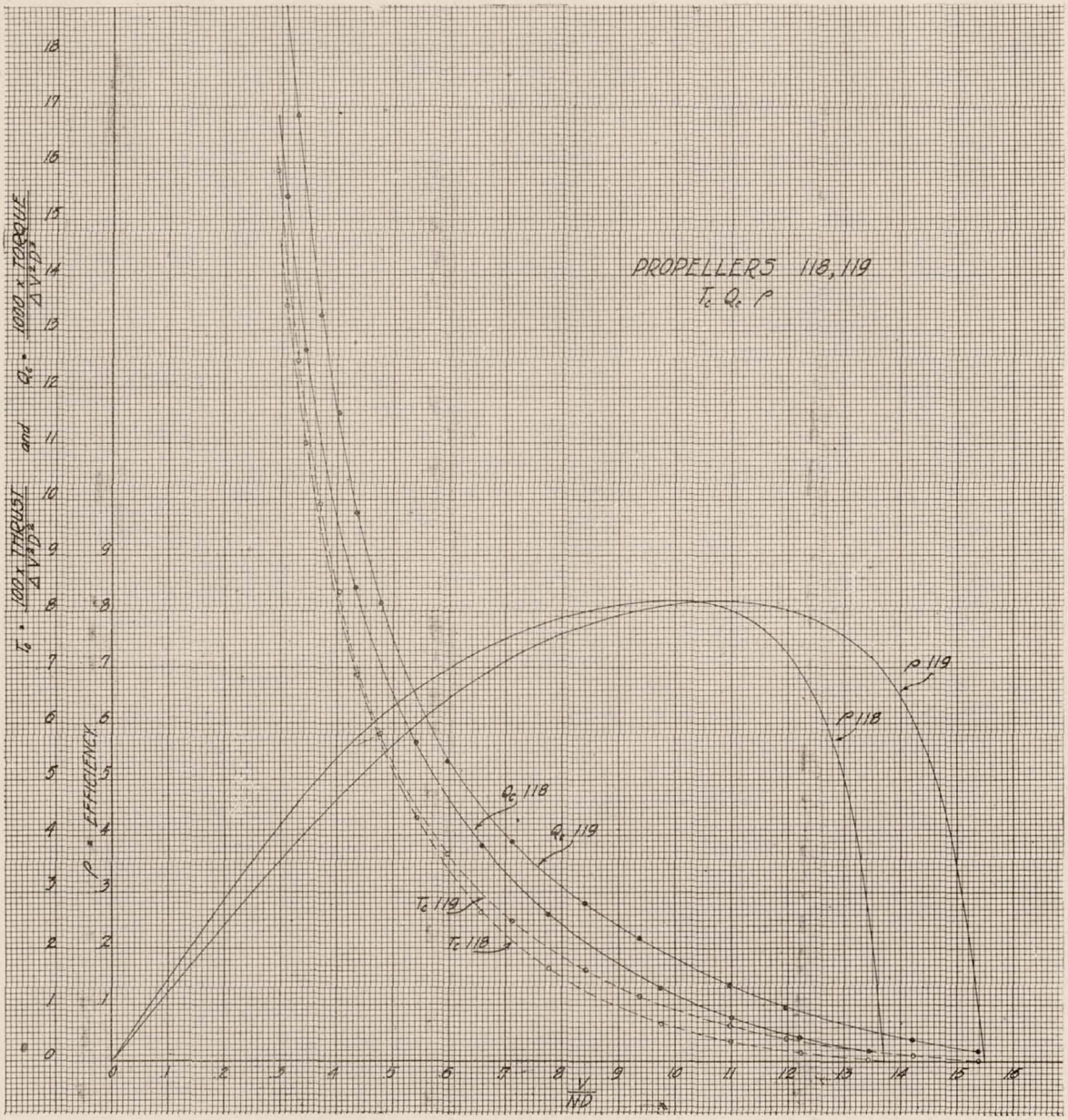

PROPELLERS 118, 119
T, Q, P
P 119
P 118
Q 118
Q 119
T 119
T 118
P = EFFICIENCY
Q = 1000 x TORQUE / ρV²D⁵
and
T = 100 x THRUST / ρV²D²
V/ND

PLATE IV.

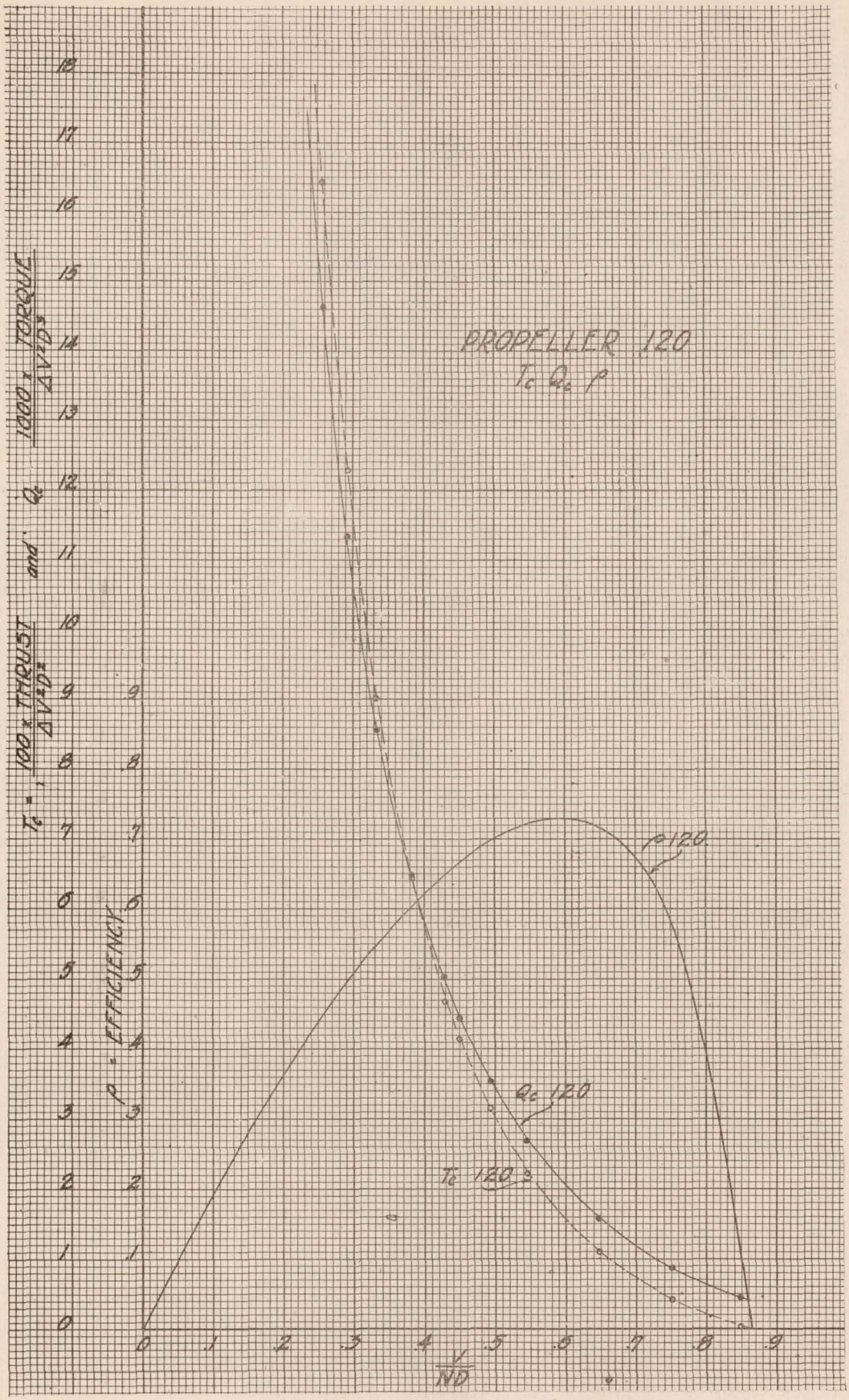

PROPELLER 120
T_c Q_c ρ
T_c = 100 × THRUST / D⁴V²ρ and Q_c = 1000 × TORQUE / D⁵V²ρ
EFFICIENCY
$\frac{V}{ND}$
ρ 120
Q_c 120
T_c 120
0 1 2 3 4 5 6 7 8 9
10 11 12 13 14 15 16 17 18

PLATE V.

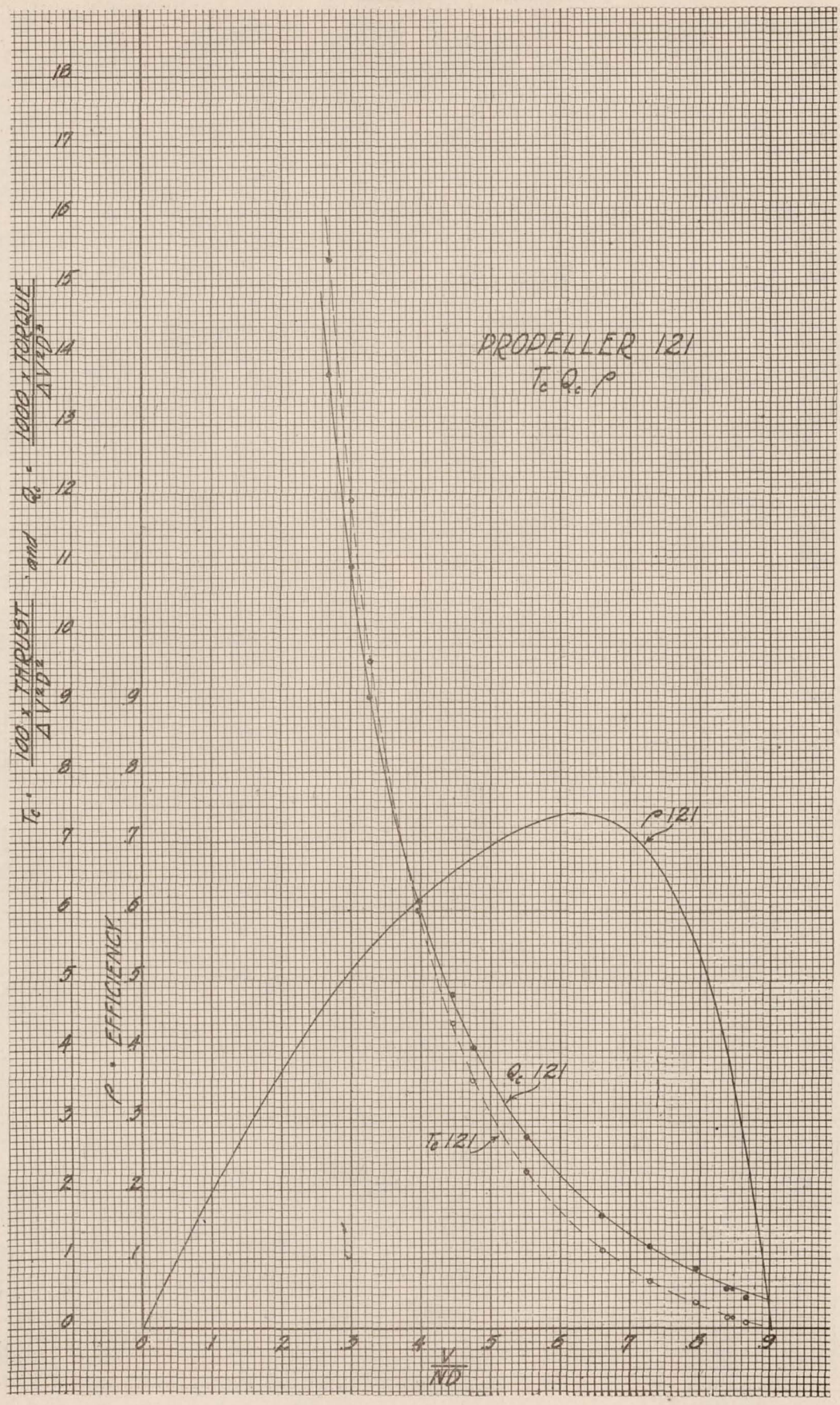

PROPELLER 121
T_c Q_c ρ
$T_c = \frac{100 \cdot THRUST \cdot mm}{\rho \cdot n^2 D^4}$
$Q_c = \frac{100 \cdot TORQUE}{\rho \cdot n^2 D^5}$
ρ · EFFICIENCY
$\frac{V}{ND}$
ρ 121
Q_c 121
T_c 121

PLATE VI.

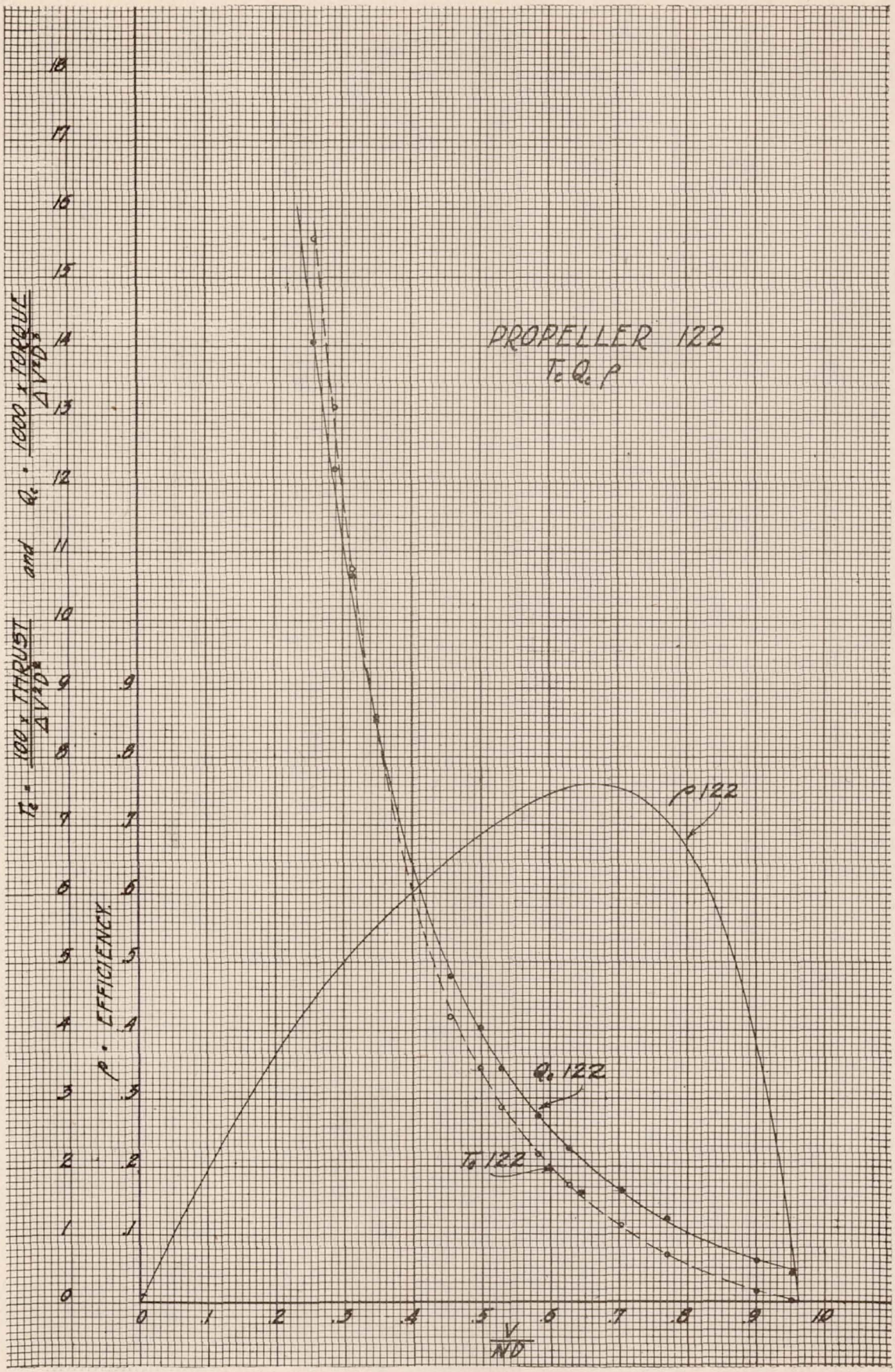

PROPELLER 122
T_c Q_c ρ
$T_c = \frac{100 \times \text{THRUST}}{\Delta V^2 D^4}$ and $Q_c = \frac{1000 \times \text{TORQUE}}{\Delta V^2 D^5}$
ρ = EFFICIENCY
ρ 122
Q_c 122
T_c 122
$\frac{V}{ND}$

PLATE VII.

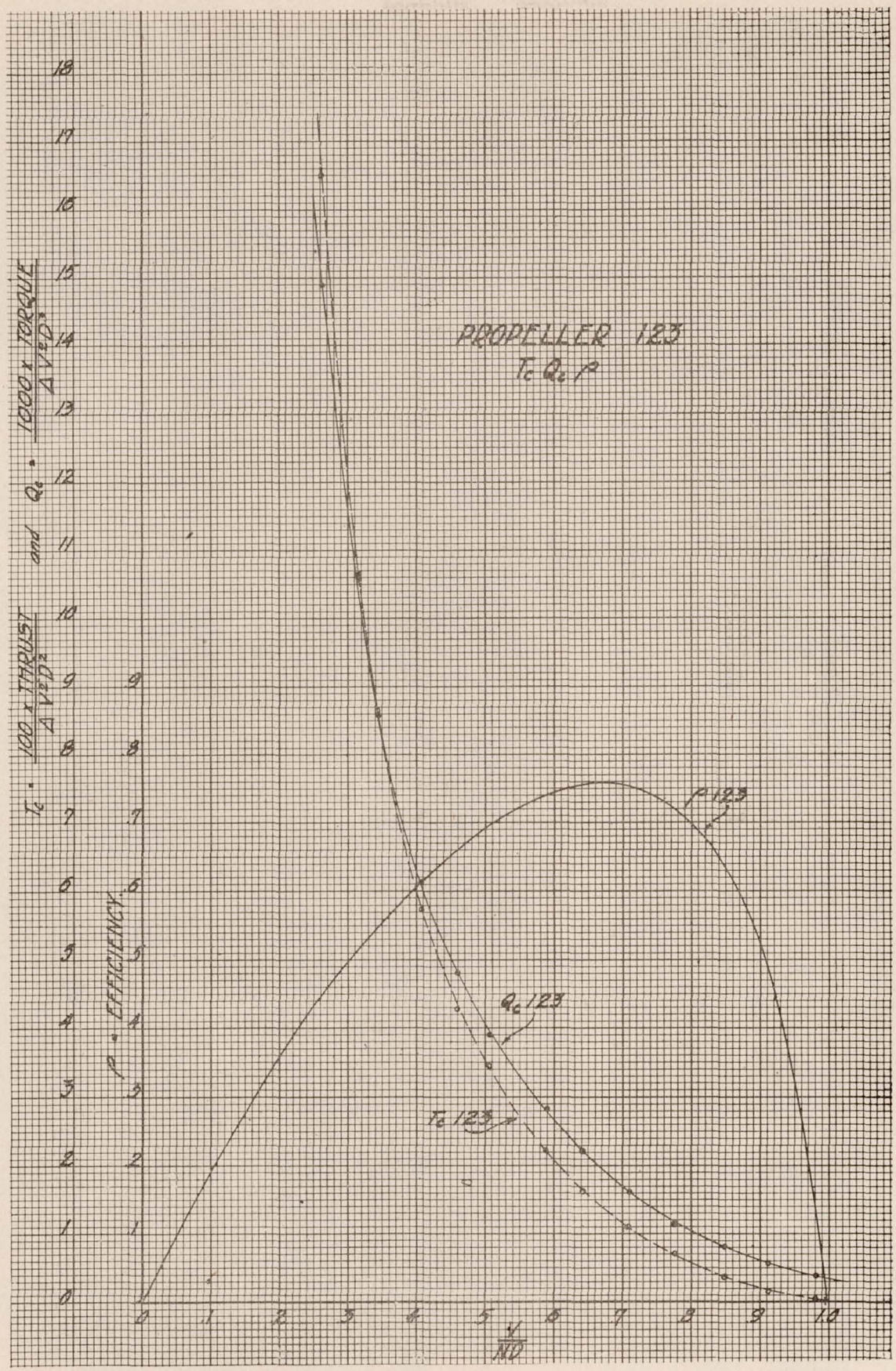

PROPELLER 123
T_c Q_c ρ
T_c · 100 x THRUST / $\Delta V^2 D^2$
and Q_c · 1000 x TORQUE / $\Delta V^2 D^5$
ρ · EFFICIENCY
ρ 123
Q_c 123
T_c 123
$\frac{V}{ND}$

PLATE VIII.

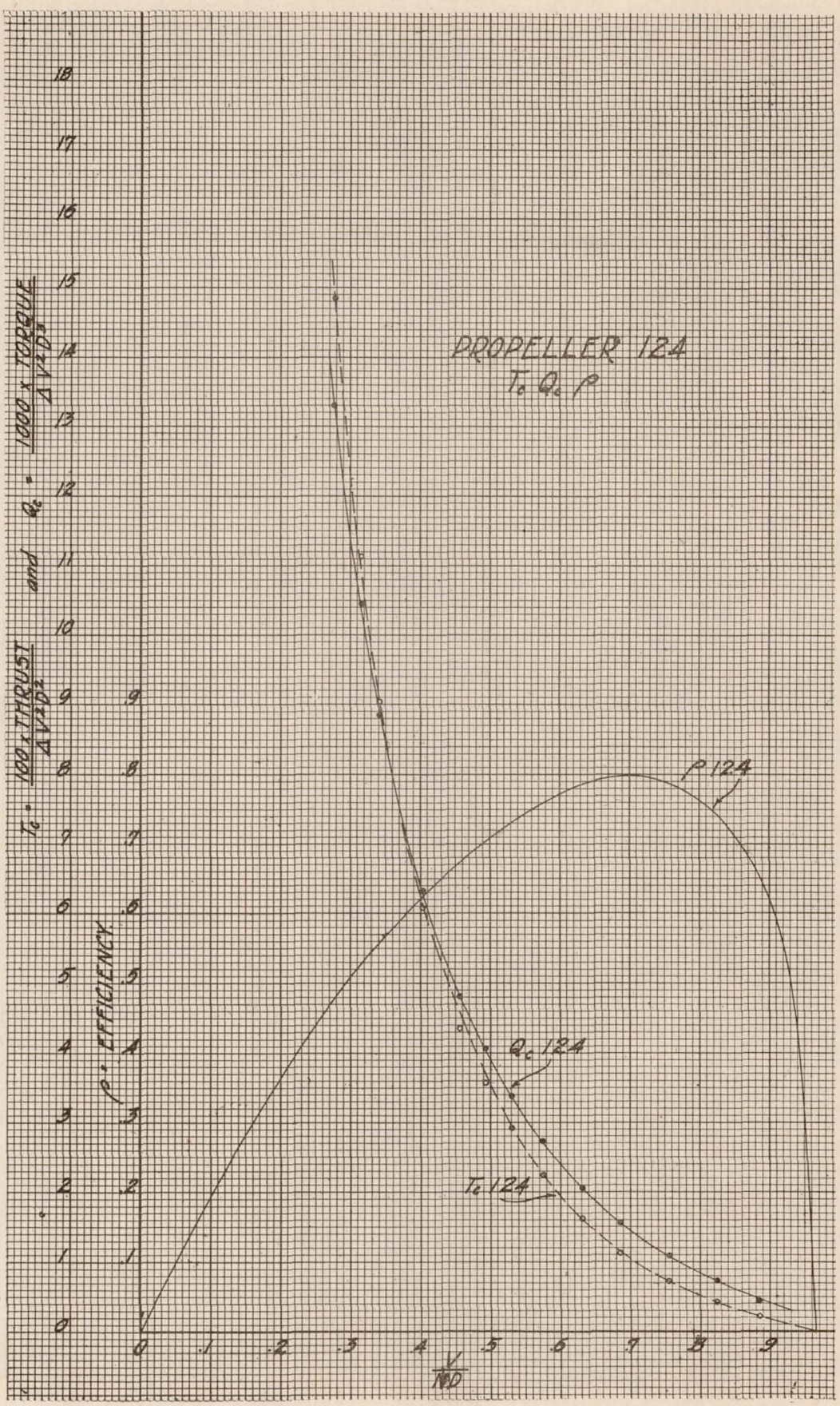

PROPELLER 124
T_c Q_c P
P 124
Q_c 124
T_c 124
$T_c = \frac{100 \times THRUST}{\Delta V^2 D^2}$
and
$Q_c = \frac{1000 \times TORQUE}{\Delta V^2 D^3}$
P = EFFICIENCY
$\frac{V}{ND}$

PLATE IX.

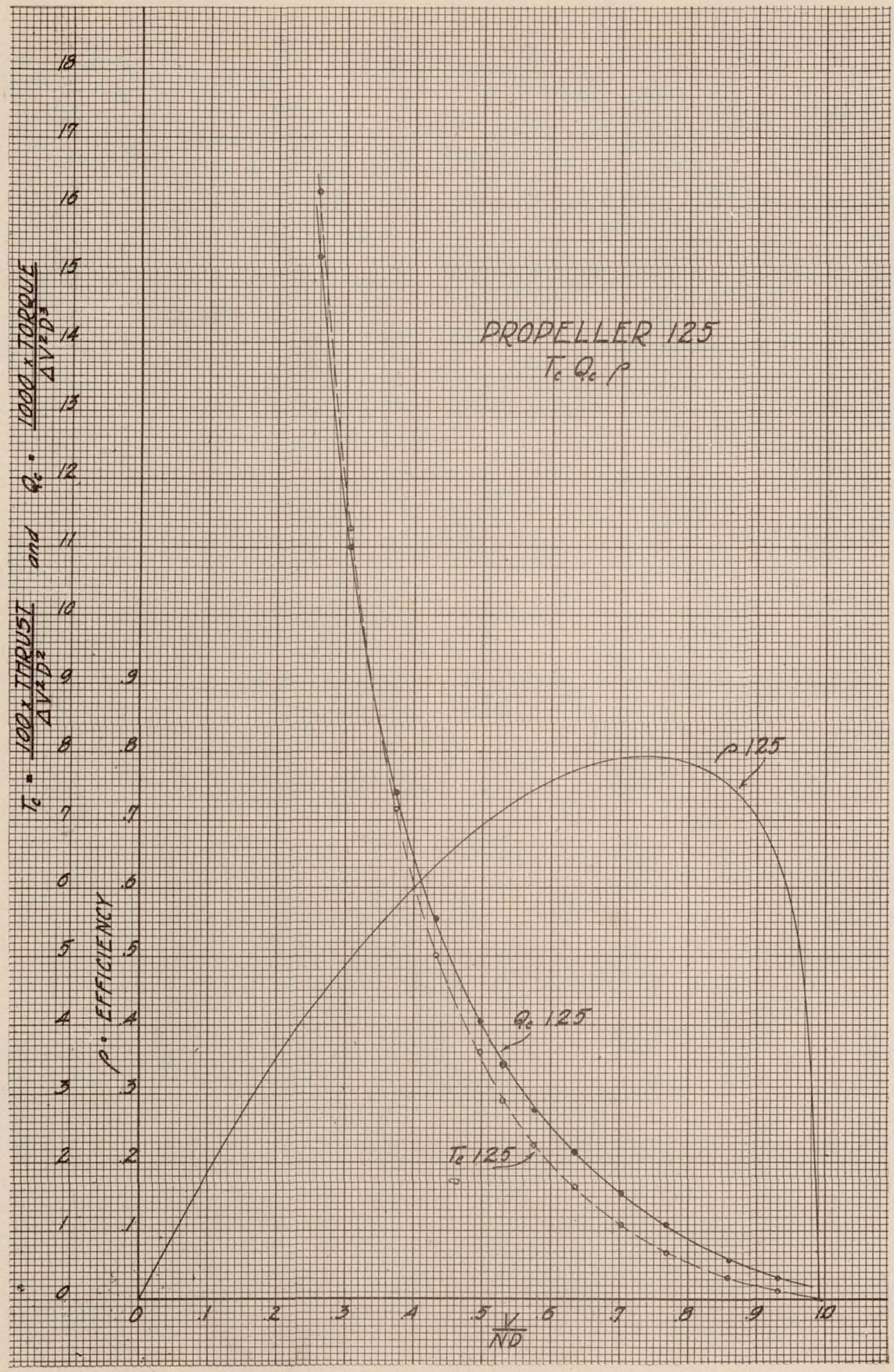

PROPELLER 125
T_c Q_c ρ
ρ 125
Q_c 125
T_c 125
T_c = 100 × THRUST / $\Delta V^2 D^2$ and Q_c = 1000 × TORQUE / $\Delta V^2 D^3$
ρ = EFFICIENCY
$\frac{V}{ND}$

PLATE X.

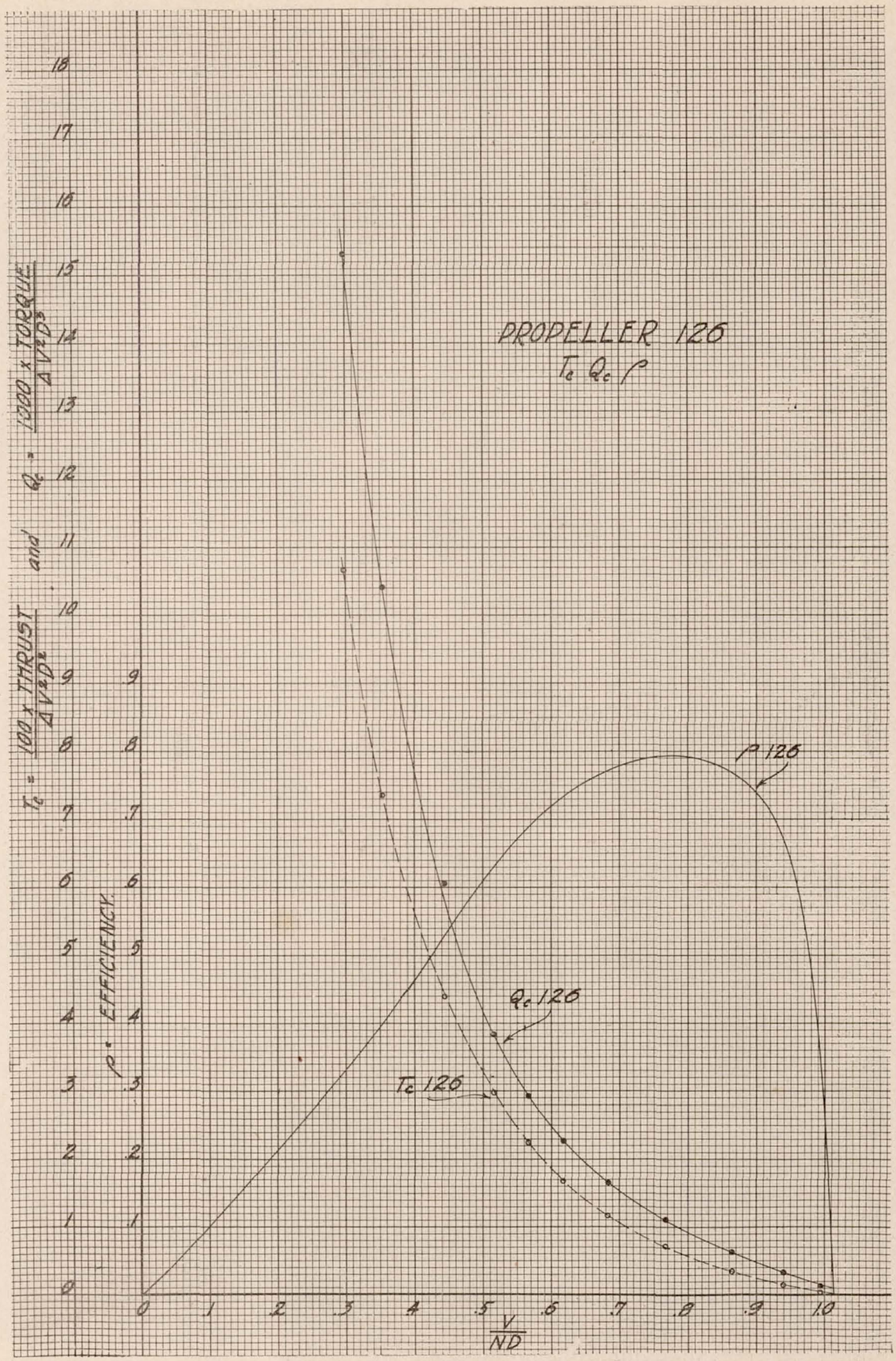

PROPELLER 126
T_c Q_c ρ
$T_c = \frac{100 \times \text{THRUST}}{\Delta V^2 D^2}$ and $Q_c = \frac{1000 \times \text{TORQUE}}{\Delta V^2 D^3}$
ρ = EFFICIENCY
ρ 126
Q_c 126
T_c 126
$\frac{V}{ND}$

PLATE XI.

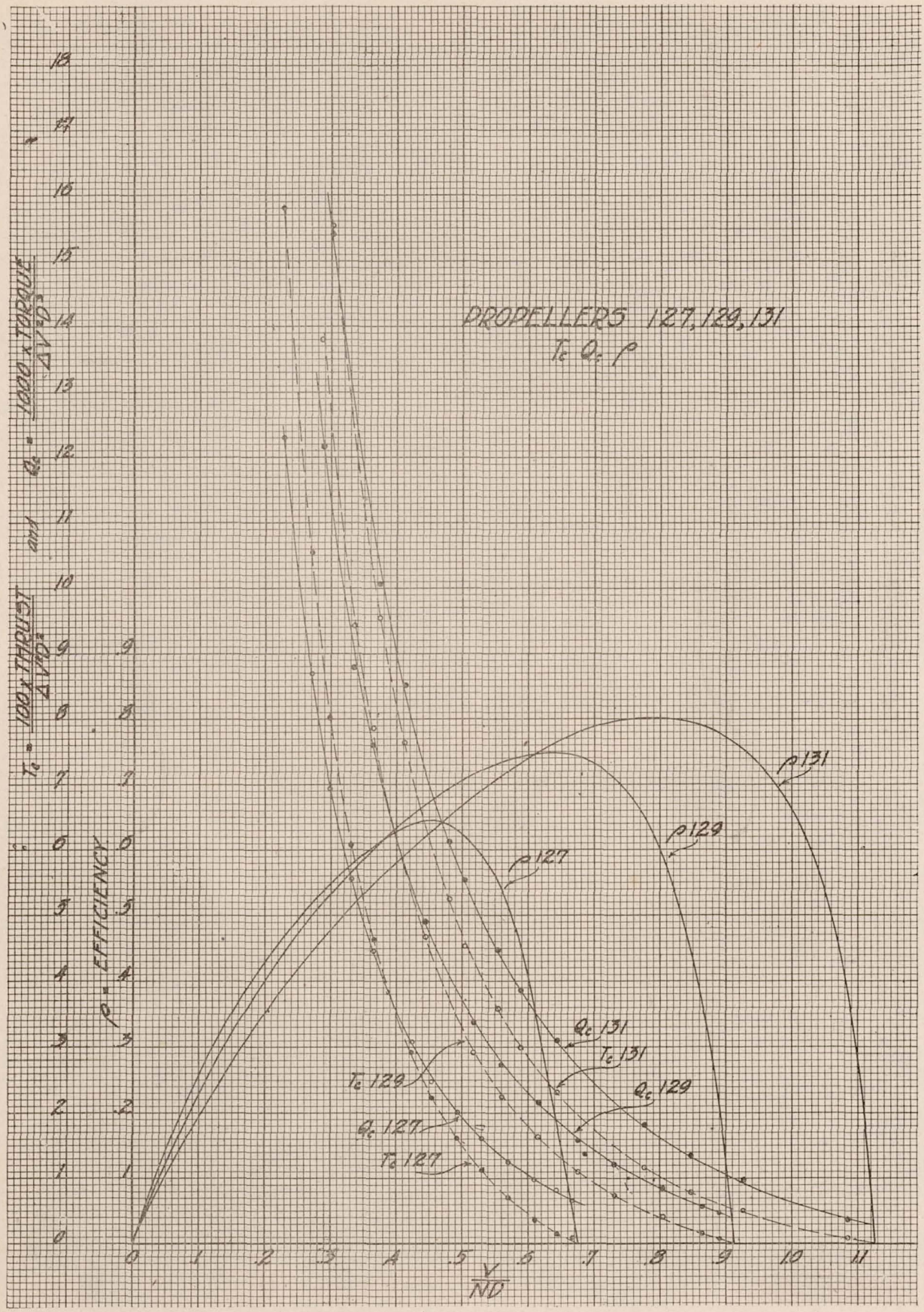

PROPELLERS 127, 129, 131
T_c Q_c ρ
T_c = 100 x THRUST / $\rho n^2 D^4$
Q_c = 1000 x TORQUE / $\rho n^2 D^5$
ρ = EFFICIENCY
$\frac{V}{ND}$
ρ 131
ρ 129
ρ 127
Q_c 131
T_c 131
Q_c 129
T_c 129
Q_c 127
T_c 127

PLATE XII.

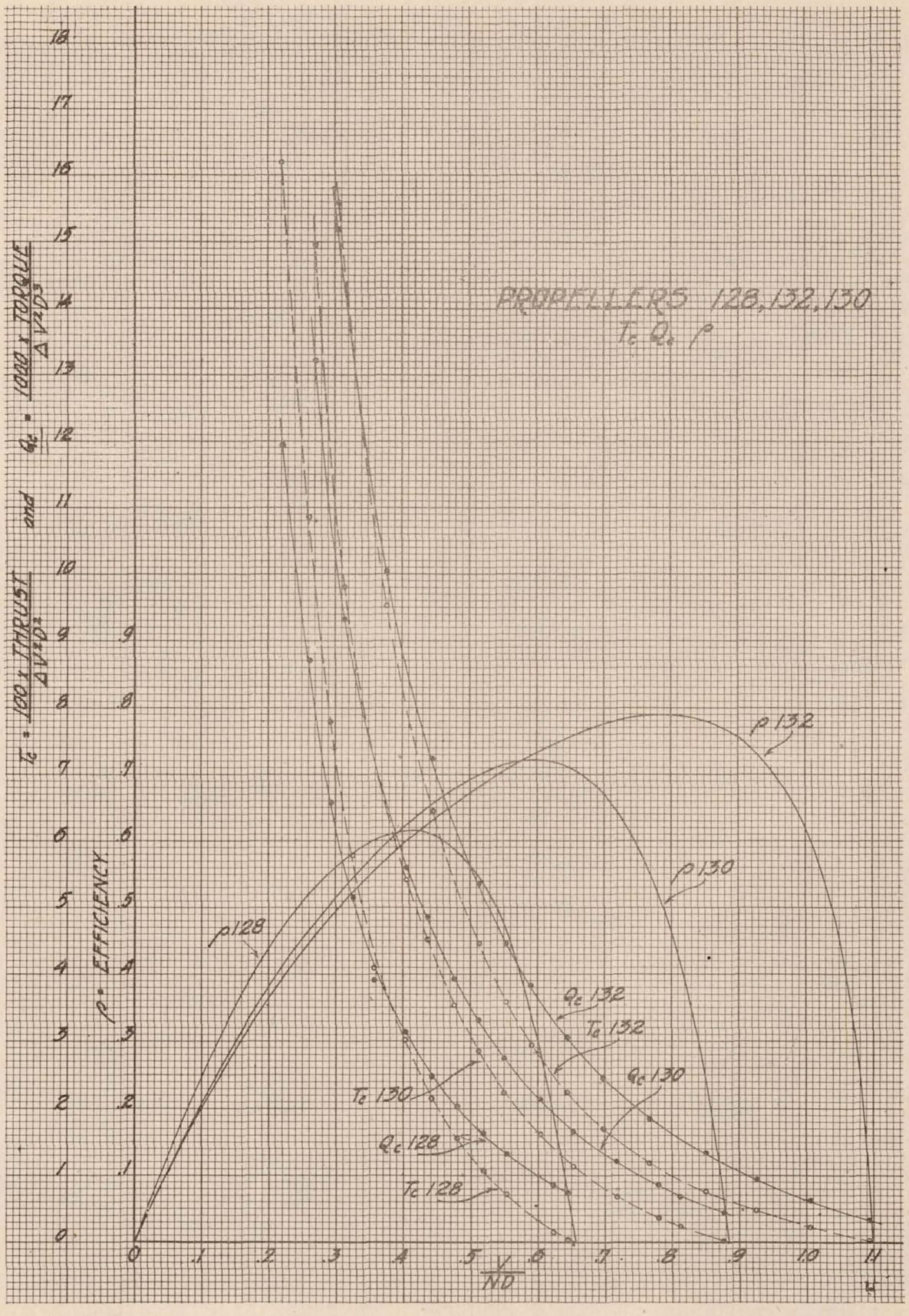

PROPELLERS 128, 132, 130
T_c Q_c ρ
$T_c = \frac{100 \, t}{\Delta V^2 D^2}$ and $Q_c = \frac{100 \, Torque}{\Delta V^2 D^5}$
ρ = EFFICIENCY
$\frac{V}{ND}$
ρ 132
ρ 130
ρ 128
Q_c 132
T_c 132
Q_c 130
T_c 130
Q_c 128
T_c 128

PLATE XIII.

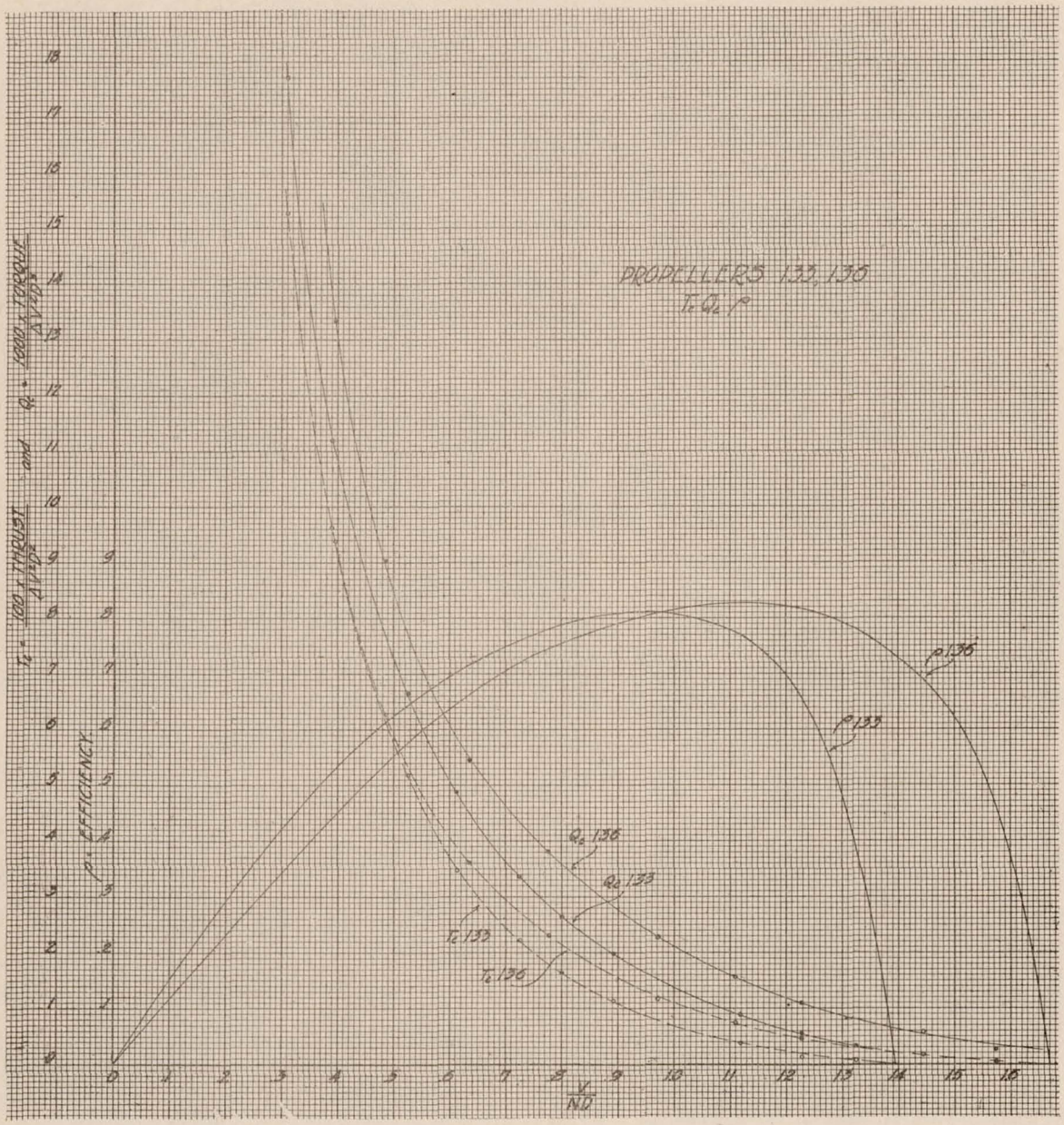

PROPELLERS 133, 136
T, Q, P
P 136
P 133
Q 136
Q 133
T 133
T 136
EFFICIENCY
THRUST, TORQUE, P
$\frac{V}{ND}$

PLATE XIV.

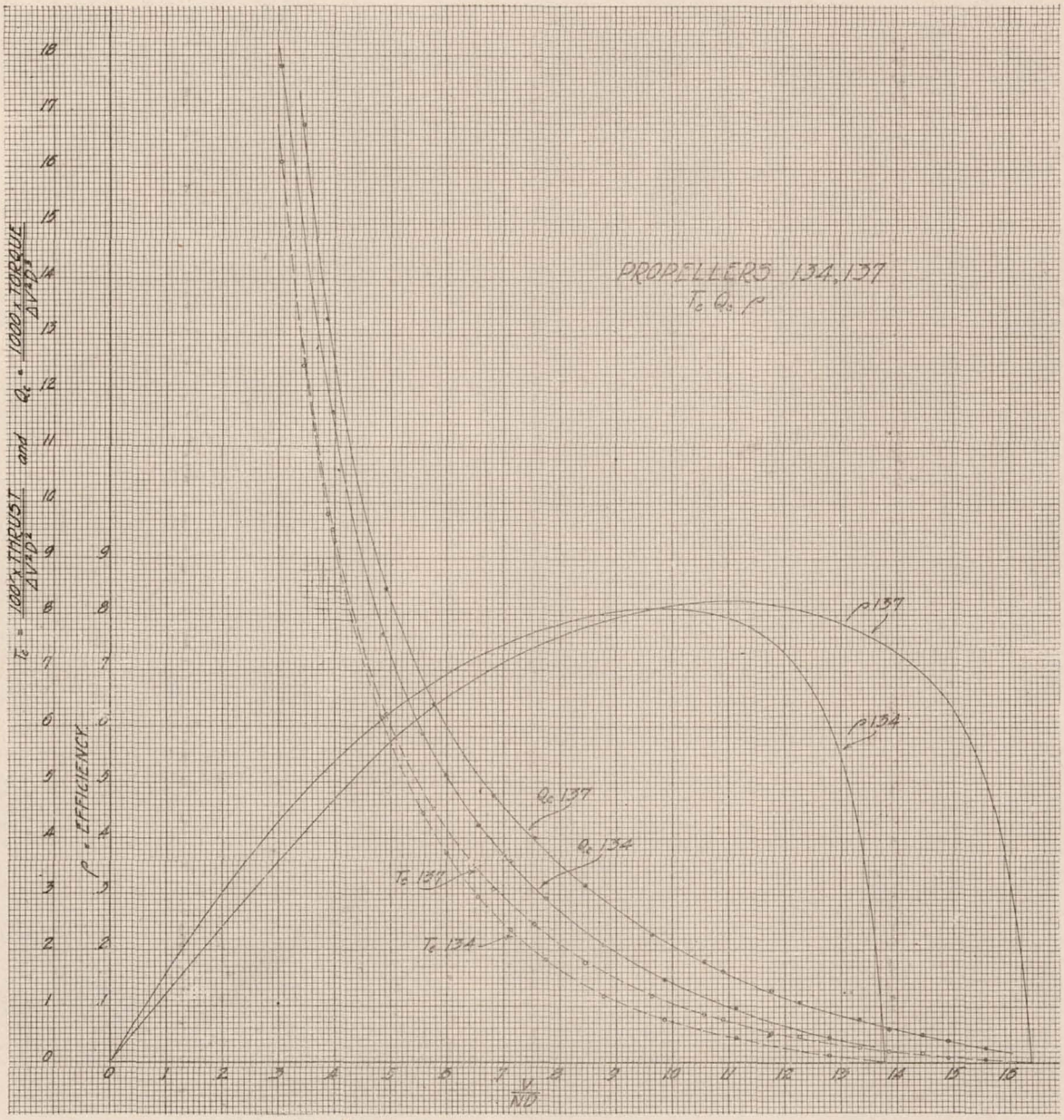

PROPELLERS 134, 137
T_c Q_c ρ
$T_c = \frac{1000 \times THRUST}{\rho V^2 D^2}$ and $Q_c = \frac{1000 \times TORQUE}{\rho V^2 D^3}$
ρ = EFFICIENCY
$\frac{V}{ND}$
ρ 137
ρ 134
Q_c 137
Q_c 134
T_c 137
T_c 134

PLATE XV.

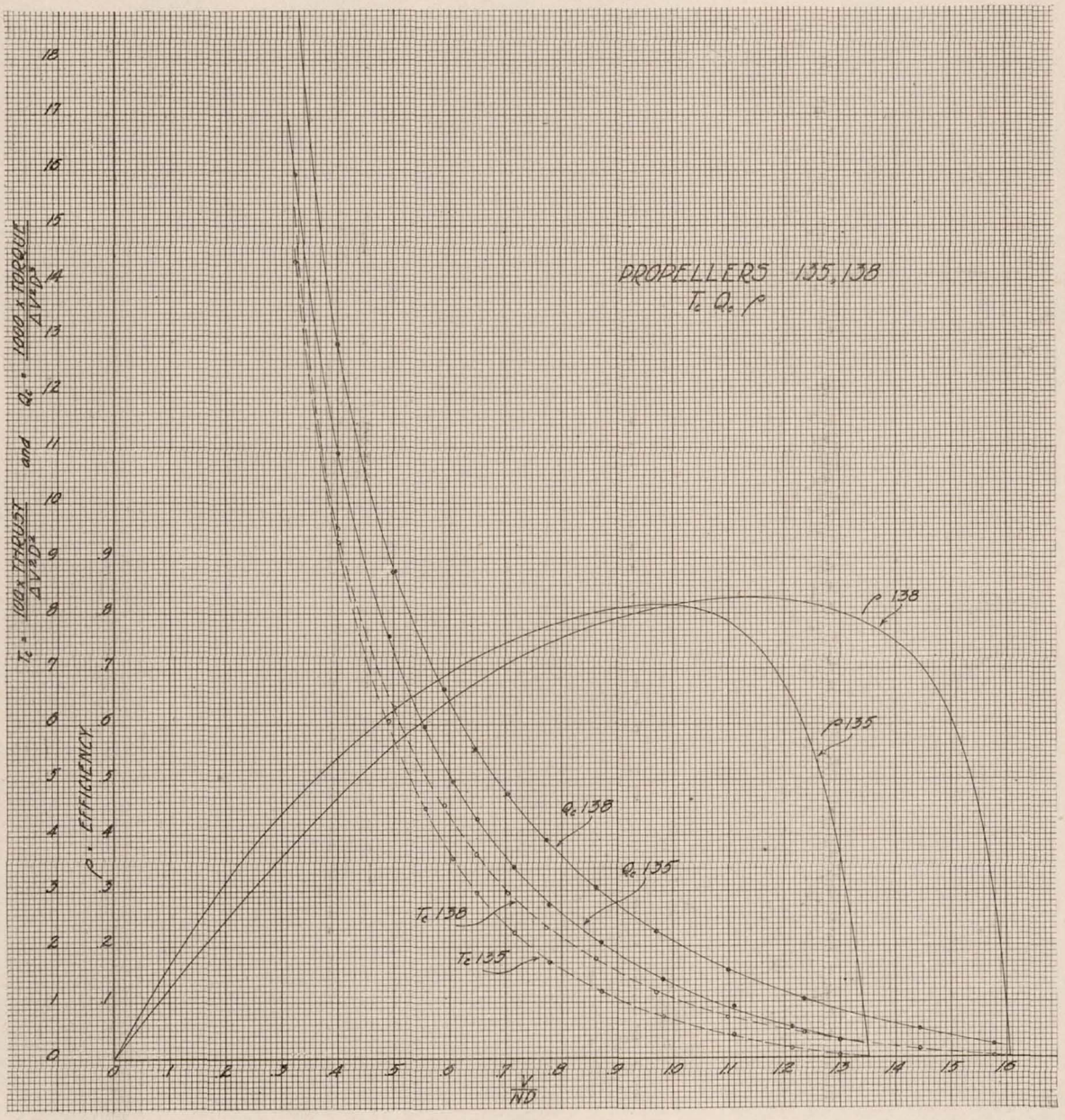

PROPELLERS 135, 138
T_c Q_c ρ
T_c · 100 x THRUST / $\rho V^2 D^2$
Q_c · 1000 x TORQUE / $\rho V^2 D^3$
and
ρ · EFFICIENCY
ρ 138
ρ 135
Q_c 138
Q_c 135
T_c 138
T_c 135
V / ND

PLATE XVI.

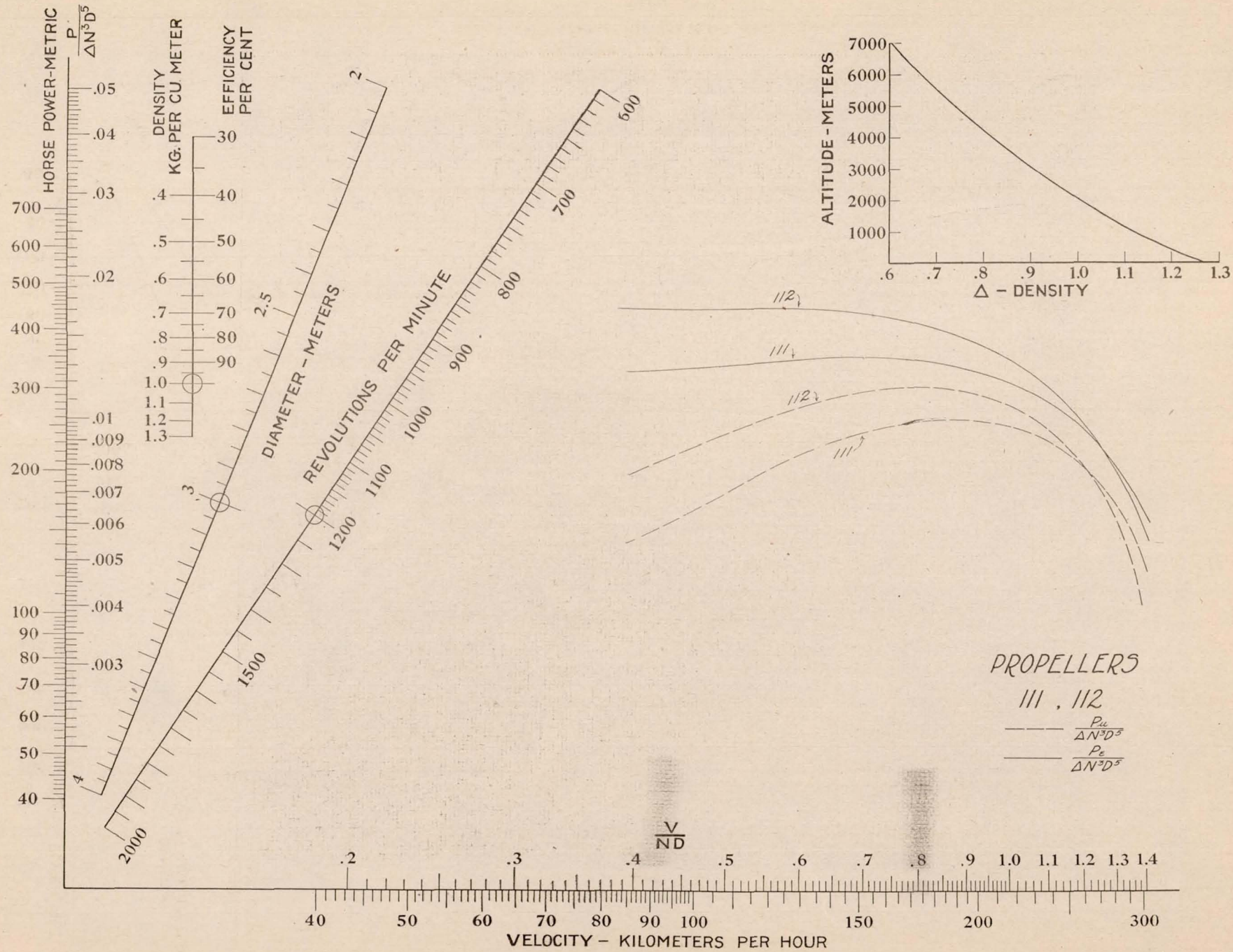

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
111 . 112
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_e}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XVII.

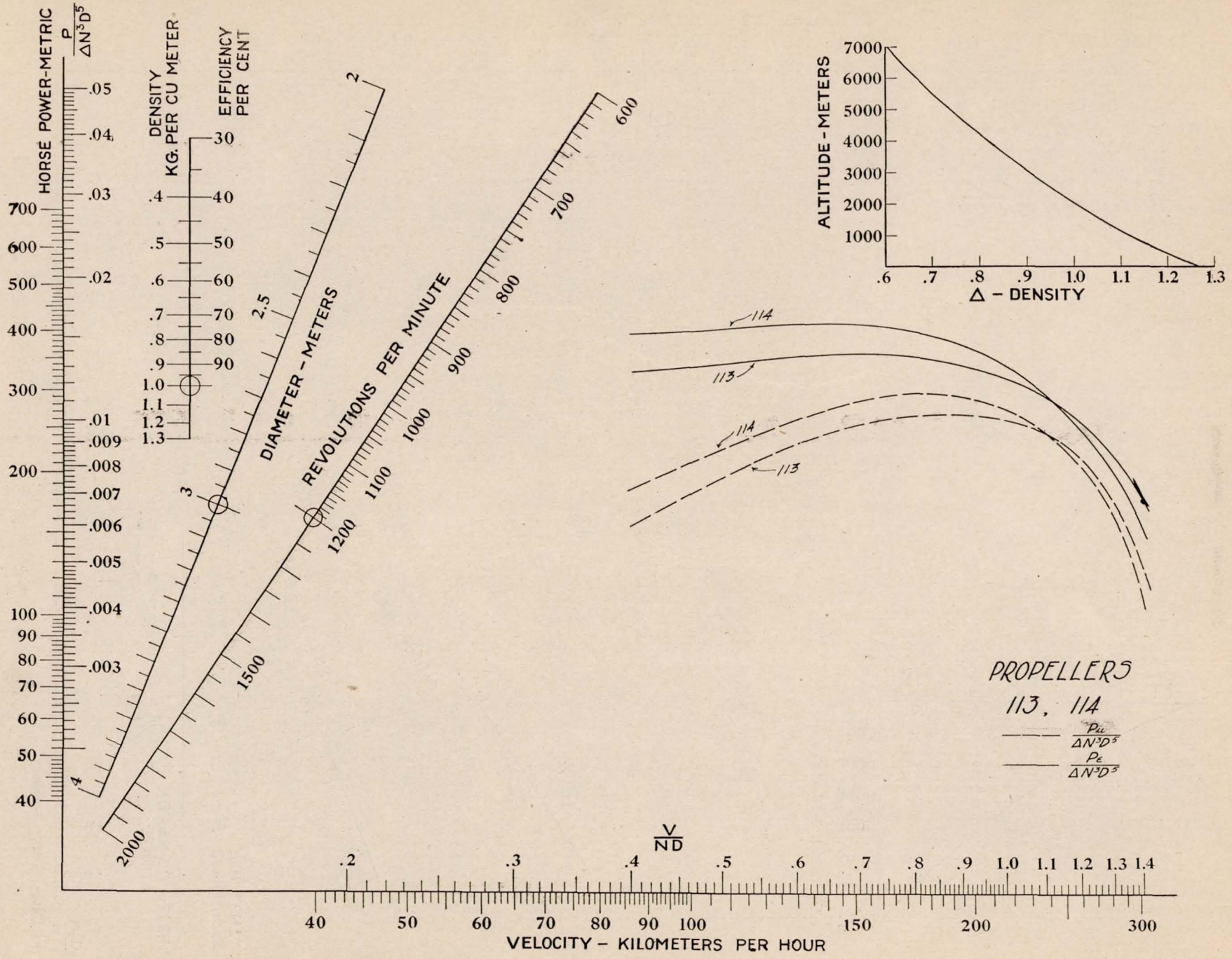

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
113, 114
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_\epsilon}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XVIII.

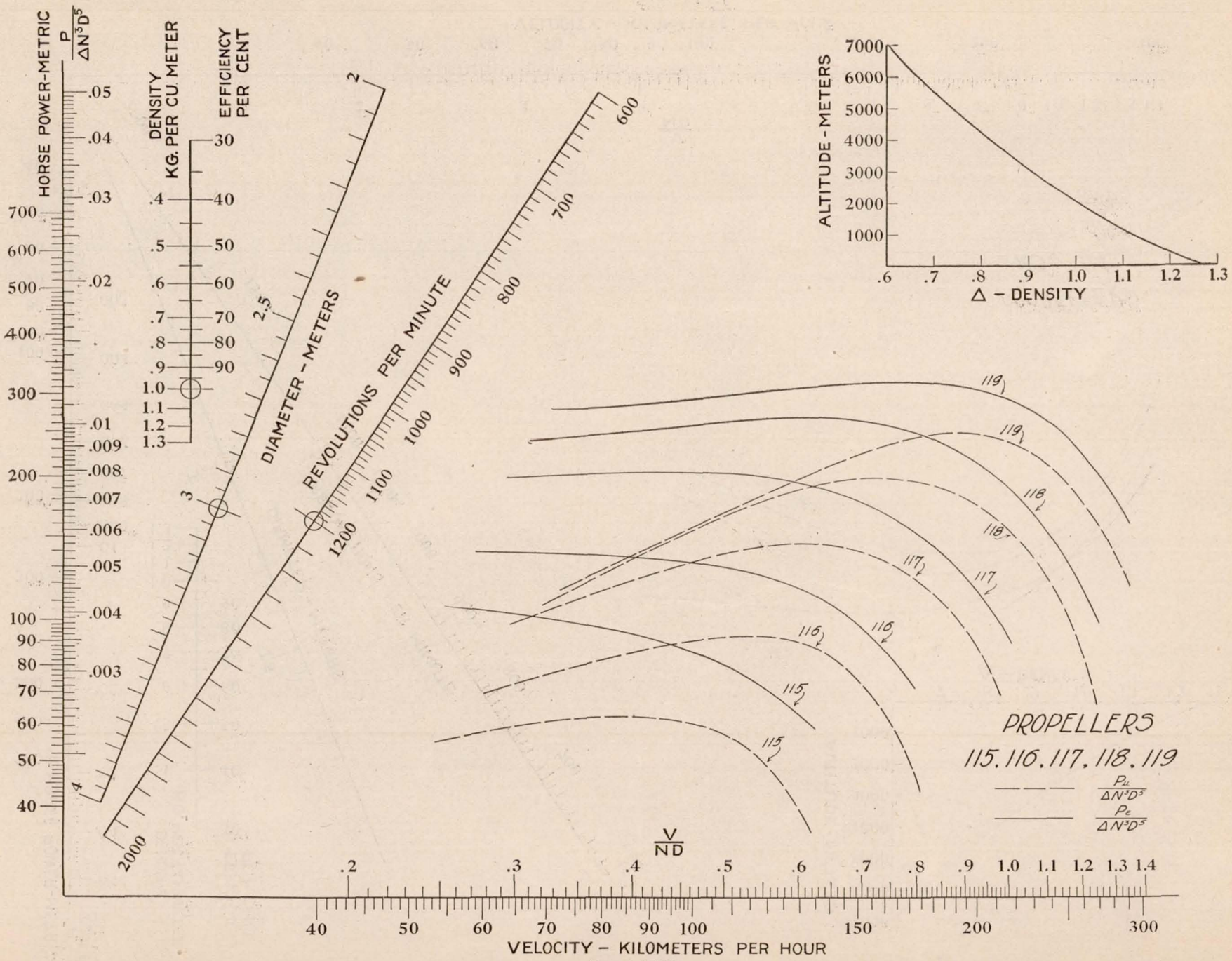

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU. METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
115. 116. 117. 118. 119
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_e}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XIX.

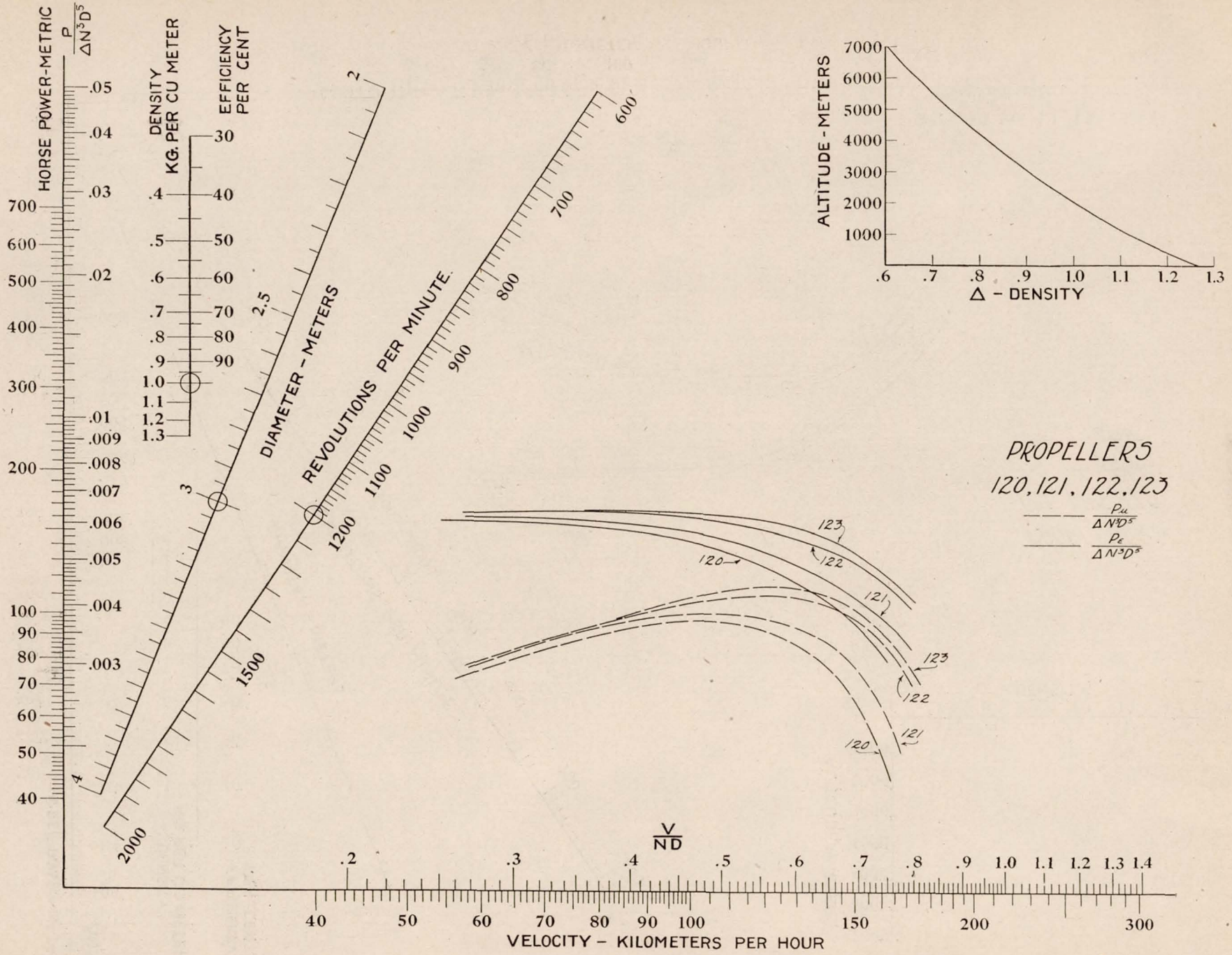

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
120, 121, 122, 123
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_\epsilon}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XX.

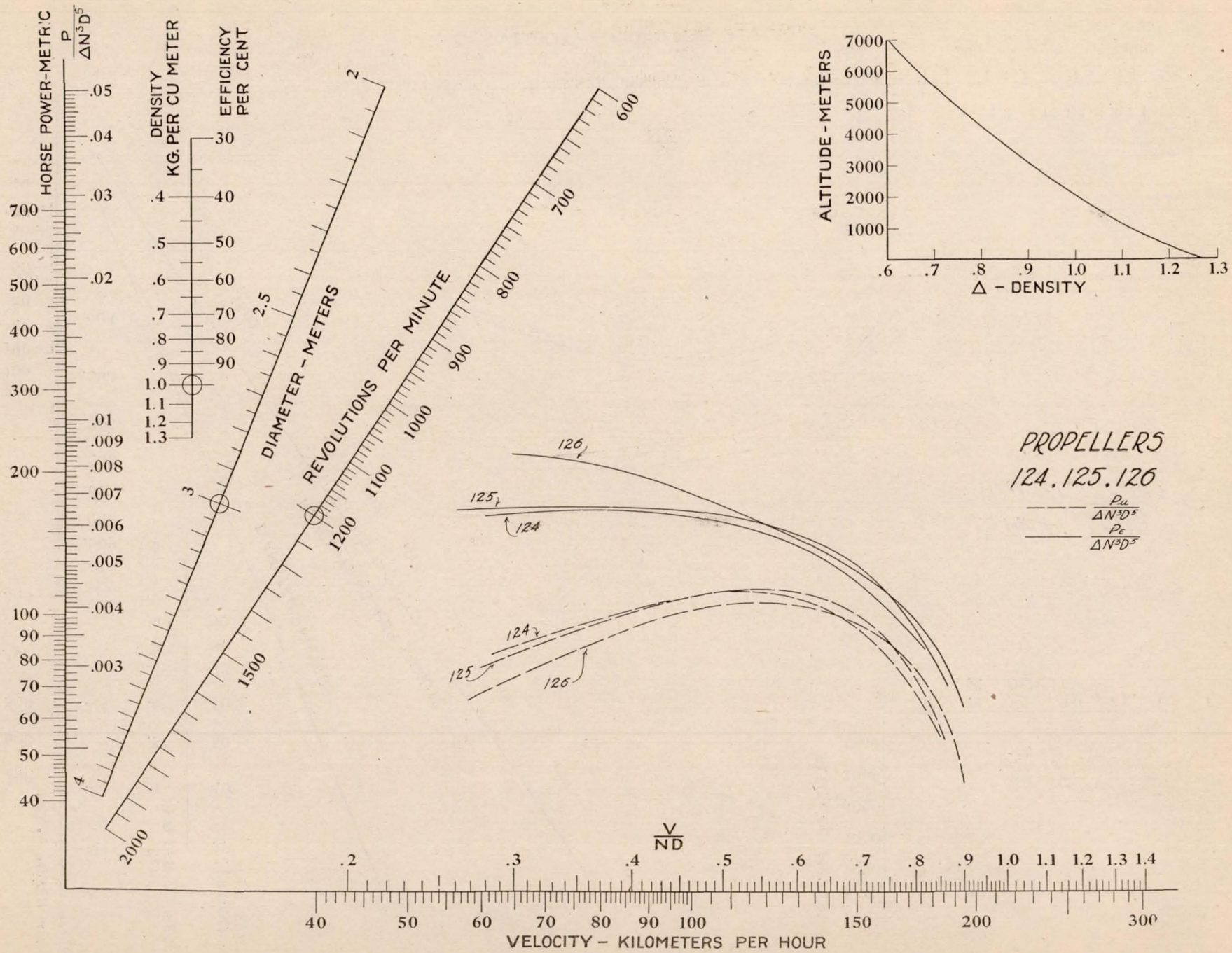

HORSE POWER-METRIC
P/ΔN³D⁵
DENSITY
KG. PER CU METER
EFFICIENCY
PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
124.125.126
Pu/ΔN³D⁵
Pε/ΔN³D⁵
V/ND
VELOCITY - KILOMETERS PER HOUR

PLATE XXI.

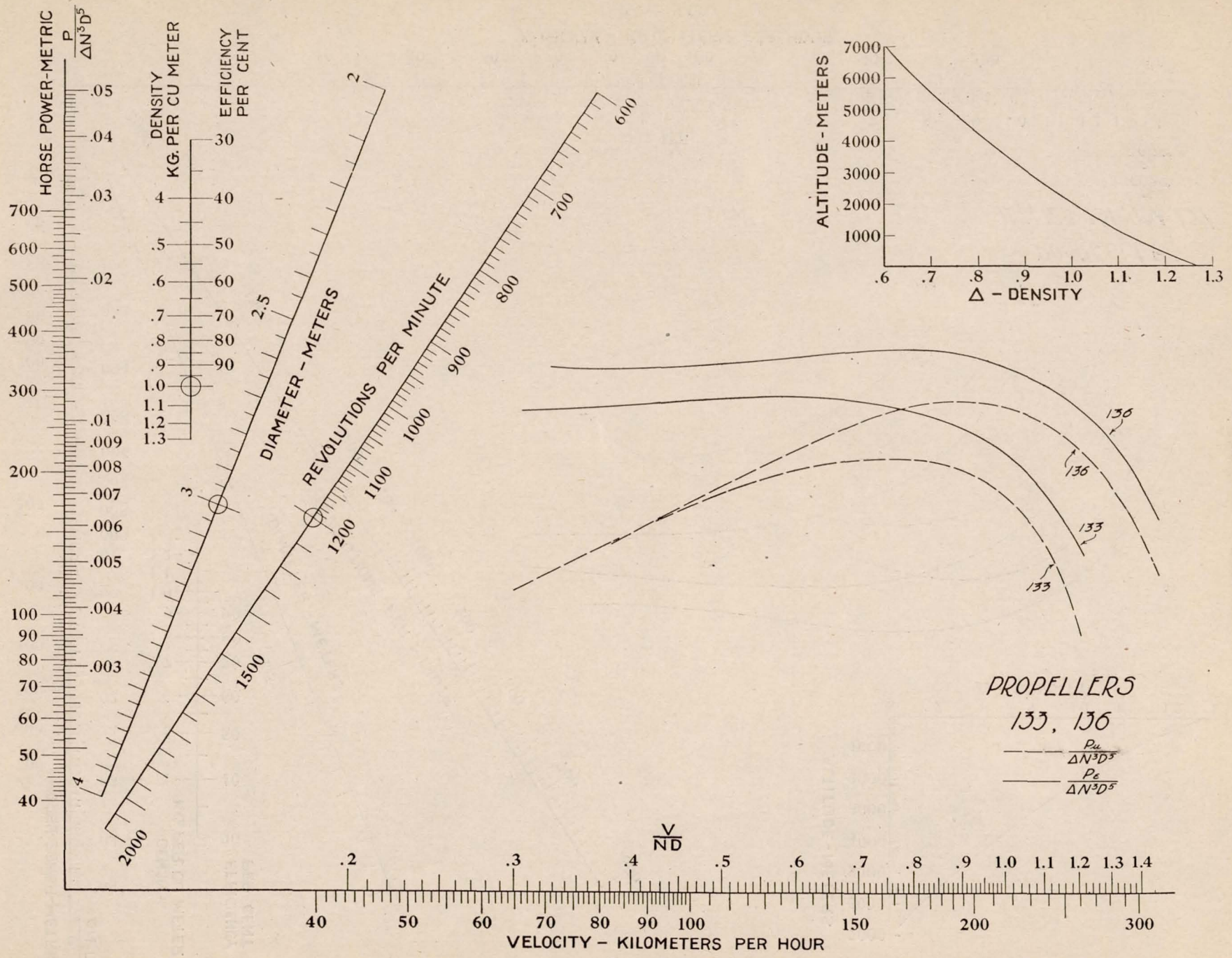

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
133, 136
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_e}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XXII.

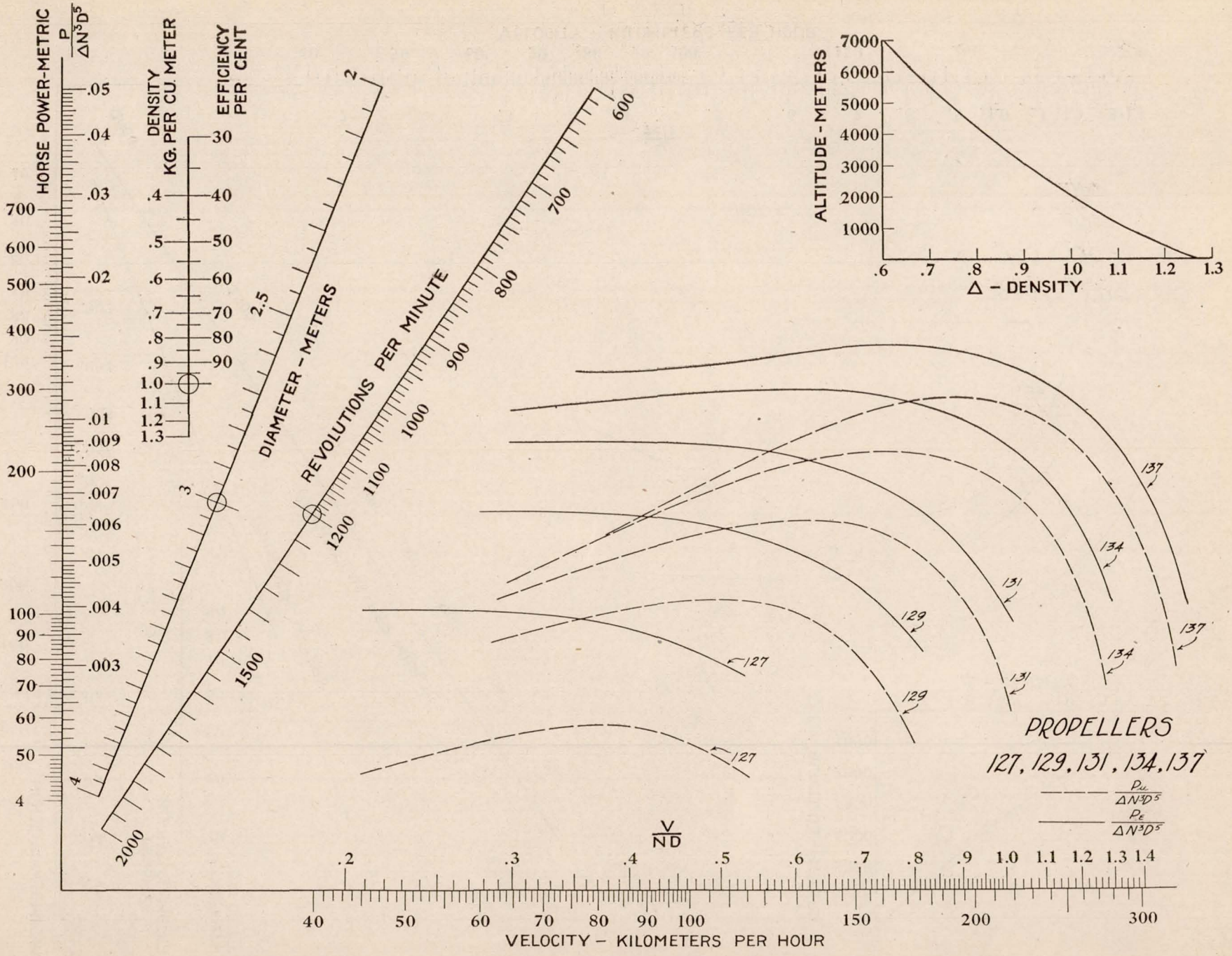

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU. METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
127, 129, 131, 134, 137
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_e}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XXIII.

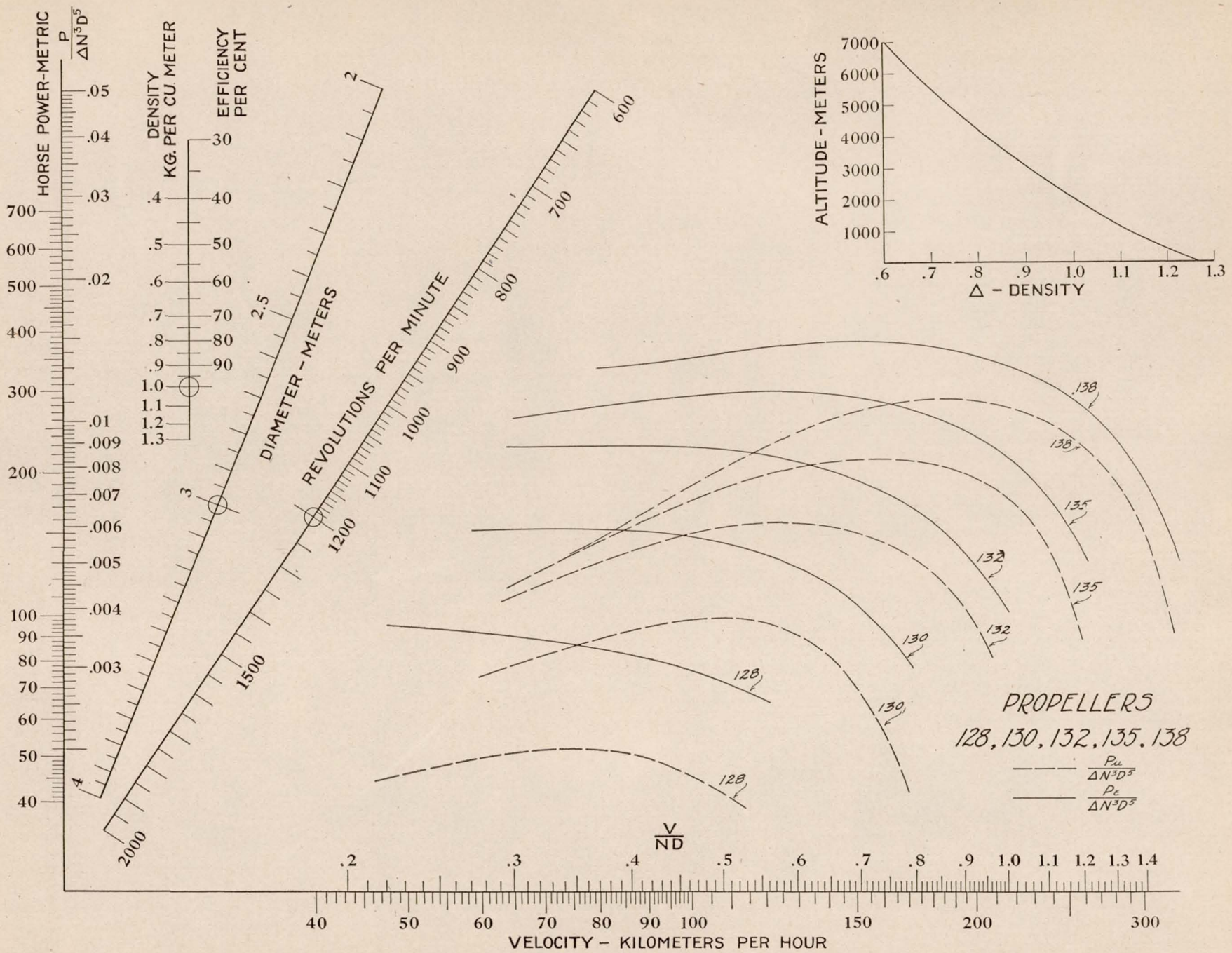

HORSE POWER-METRIC $\frac{P}{\Delta N^3 D^5}$
DENSITY KG. PER CU METER
EFFICIENCY PER CENT
DIAMETER - METERS
REVOLUTIONS PER MINUTE
ALTITUDE - METERS
Δ - DENSITY
PROPELLERS
128, 130, 132, 135, 138
$\frac{P_u}{\Delta N^3 D^5}$
$\frac{P_e}{\Delta N^3 D^5}$
$\frac{V}{ND}$
VELOCITY - KILOMETERS PER HOUR

PLATE XXIV.

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REPORT No. 65

THE KILN DRYING OF WOOD FOR AIRPLANES

By HARRY D. TIEMANN
Engineer in Forest Products

153215—S. Doc. 166, 66-2——24

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FOREWORD.

This publication is one of a series of eight monographs prepared by the Forest Products Laboratory of the Forest Service, United States Department of Agriculture, for publication by the National Advisory Committee for Aeronautics.

The purpose of the series of monographs is to discuss in detail the various requirements of wood for use in aircraft, and also to make public some of the results obtained in the experimental and testing work of the Forest Products Laboratory undertaken for the Army and Navy during the war.

The subjects discussed in the series will include: (1) Kiln drying of airplane woods, (2) the effect of kiln drying on strength, (3) the care of airplane stock, (4) the composition and use of glues, (5) the manufacture and testing of ply wood, (6) wood in airplane construction, (7) moisture-resistant finishes, and (8) wood airplane parts.

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REPORT No. 65.

THE KILN DRYING OF WOODS FOR AIRPLANES.

By HARRY D. TIEMANN.

I. INTRODUCTION.

KILN DRYING UNDER WAR CONDITIONS.

The exigencies of the war and the scarcity of air-dried material necessitated the kiln drying, immediately from the green condition, of practically all of the wood used in the United States for airplanes. This was a complete reversal of established practice and, from the standpoint of commonly accepted beliefs, was a dangerous innovation. England and France specified against "kiln drying" airplane woods, but in certain instances permitted "conditioning," that is, allowing the lumber to remain in a slightly heated dry room, usually at 25° C. (77° F.) or 30° C. (86° F.). A higher moisture content, however, was allowed there than in this country, the British requirement being 15 per cent for most woods and 18 per cent for ash, with an allowable variation of 3 per cent.

Perhaps the term "kiln drying" has an unfortunate association with lime or pottery or brick kilns, in which the material is baked. It must be admitted that the results formerly obtained in kiln drying lumber tended to create a prejudice in favor of the time-honored methods of slow air seasoning. The application of artificial heat, in the absence of thorough scientific knowledge of the principles involved and the development of a correct technique, resulted in much injury to the wood in checking, loss of strength, and warping.

Within the last 10 years the United States has taken the lead in placing the subject on a technical and scientific basis. It is now a well-established fact that many species of wood can be dried from the green state with better results than can be obtained by the irregular and unscientific method of air drying. While the chief reason for kiln drying in the past has been a saving of time, as the methods are perfected the superiority of the results obtained, from a quality standpoint, will be an increasingly important consideration.

Ordinary air seasoning, on account of its vicissitudes due to inability to control the process, is far from an ideal method of conditioning, even though the element of time did not enter into the question. This is particularly true for the more refractory and the more valuable woods and for all woods which are required for very exacting purposes, such as airplanes. It should not be overlooked, however, that a very gradual seasoning at air temperature, provided conditions are properly controlled, can not be excelled in its effect upon quality. This is true for the reason that the moisture difference between the outer surface and the interior is thereby kept at a minimum, so that no appreciable stresses are brought about by unequal shrinkages.

Because of the shortcomings of air seasoning various auxiliary methods have been sometimes used, such as preliminary soaking for years in ponds of water (still practiced in parts of Japan and Sweden) or burying in the ground or in manure.

Although the popular prejudice against kiln drying has not been entirely removed, especially in European countries, this method of conditioning lumber is now a scientific art and not a haphazard guess. Exhaustive strength tests made recently by the Forest Products Laboratory have shown beyond question that properly kiln-dried wood is just as strong, tough, and stiff as the best air-dried material.

Kiln drying for special purposes, such as airplanes, should be looked upon as a highly technical art. Lumber can be much more easily injured in a dry kiln than if left to dry in a shed exposed to the air, and unless the kiln drying is properly conducted air drying is safer. But if the kiln is in charge of a techincal expert, and the process is carried on in a scientific manner, kiln drying is greatly to be preferred to ordinary air drying.

The exigencies brought about by the war left no choice but to use kiln-dried material. To air dry Douglas fir wing beams requires ordinarily from 12 to 18 months. They may be kiln dried in 18 to 24 days. To air dry hardwood propeller stock takes at least one and preferably two years. The same material can be kiln dried and brought to equally good condition in a month's time. Air drying was, under the circumstances, wholly out of the question.

QUALITIES OF PROPERLY DRIED WOOD.

Whether kiln dried or air dried, the success of the seasoning process depends upon the extent to which the following requirements are met.

The material should be free from surface and end checks. Such checks are not necessarily visible. They may develop in the drying process and close up again when it is completed. This does not rectify the injury; the checks are still present, though pressed tightly together. Such material is unsuitable for airplanes.

The wood must be entirely free from internal checks, or "honeycombing" (see Pl. II). Such checks may be invisible upon the surface, but are evident when the stick is cut into.

The wood must be free from "casehardening." Casehardening is due to internal stresses. It is discussed in detail on page 19. Casehardened wood warps and cups when resawed or cut into small pieces (see Pl. III). Sometimes the internal stresses may be only temporary, due to unequal moisture distribution, and disappear when the moisture equalizes. In that case they are not serious, provided resawing does not take place in the meantime. Or they may remain in the wood indefinitely. Such stresses are of course detrimental.

The moisture must be uniformly distributed. In poorly dried lumber, portions of it may still retain some free water while other portions are very dry. Or there may be a wet core in the center while the outside is dry (see Plate IV, fig. 1.) Both conditions are extremely bad, as it will require an excessively long period before the moisture will equalize, and in the equalizing process the wood is subject to all the dangers which it faced in the original drying. Wood should never be manufactured into finished parts while the moisture distribution is unequal, since the relative dimensions are certain to change when the moisture finally equalizes, so the parts will no longer correspond in size.

The strength and toughness of the wood must be at a maximum. High temperatures and excessive internal stresses during drying cause injury to the strength and toughness. The effects vary considerably with different species. Softwoods as a rule are less subject to injury of this kind than are hardwoods. Excessive drying may of itself cause brittleness, even though the wood has subsequently reabsorbed moisture. For this reason the drying must not be carried too far. The requirements for airplanes are so exacting that material which would be entirely satisfactory for commercial uses might be altogether unsuitable for airplanes. Visual inspection of the dried wood is inadequate, since injury to strength may occur without any defect visible to the eye. Hence the drying process itself must be closely watched and controlled.

The wood should be free from excessive collapse and free from warping. Collapse is a sinking in of the fibers (see Plate IV, fig. 2) much in the same way that a rubber tube collapses when subjected to an internal vacuum. Certain species are peculiarly subject to this phenomenon.

In ordinary commercial work, drying without loosening the knots or causing them to protrude is a prime consideration. In conditioning airplane stock it is of course unnecessary to give consideration to this point, since all knots of any consequence are excluded.

Shrinkage should be the minimum consistent with securing the other qualities. It is not an independent factor; in fact, the very conditions most favorable for least shrinkage are also those most favorable to the development of internal stresses and casehardening. Shrinkage, if not unreasonable in amount, must therefore be largely disregarded.

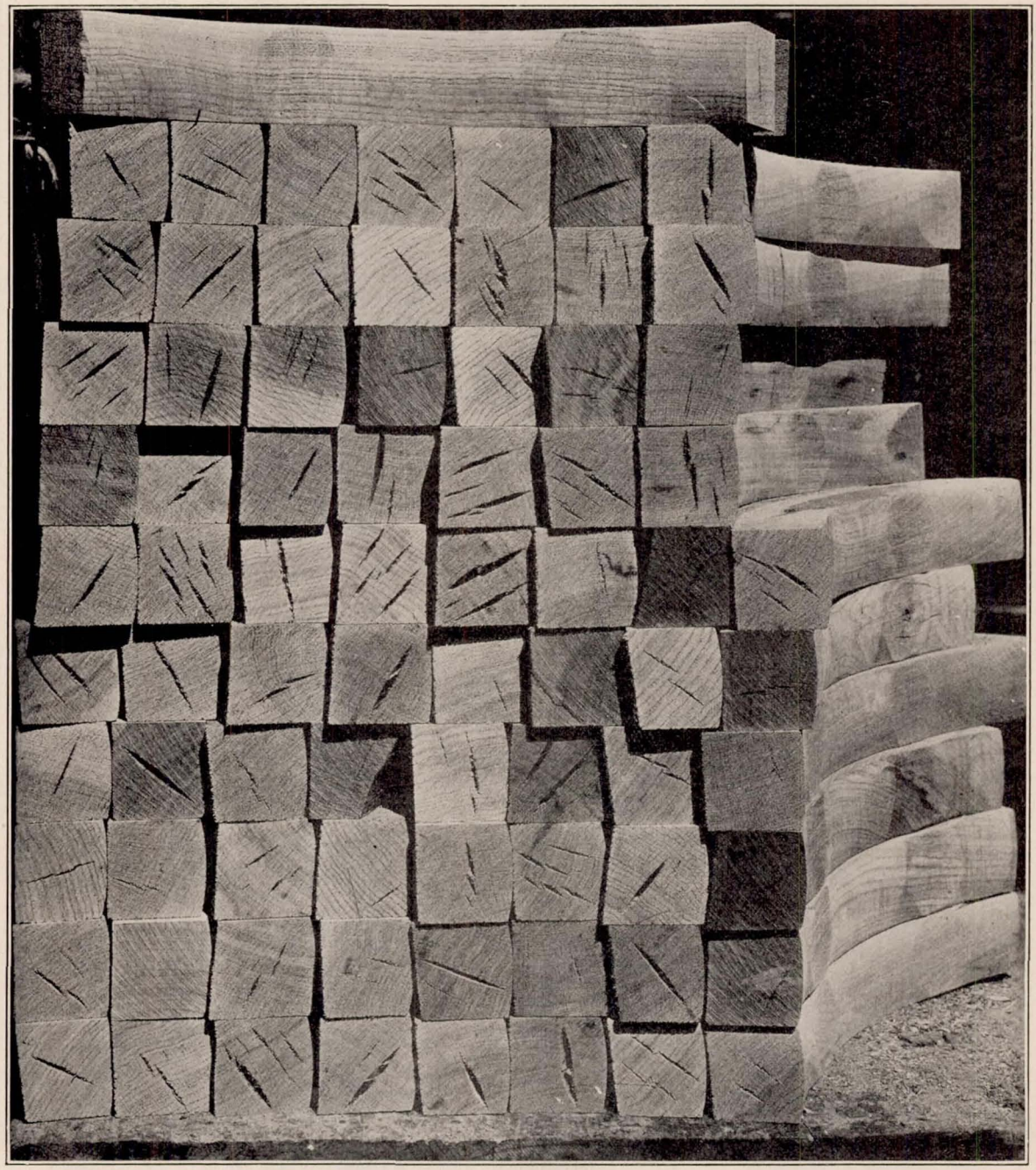


FIG. 1.—STOCK WHICH HAS BECOME SURFACE CHECKED IN AIR DRYING.



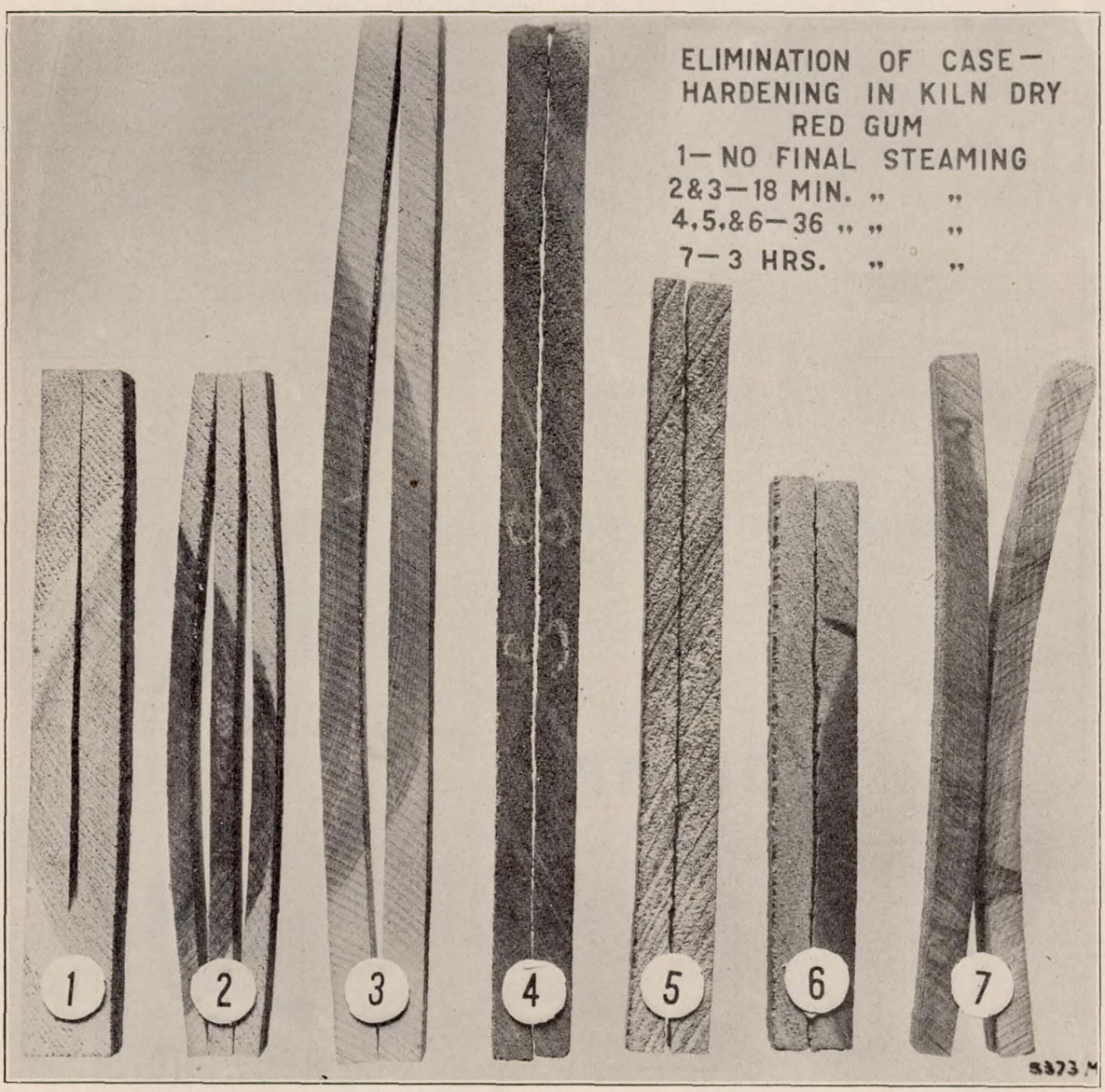
FIG. 2.—THE SAME MATERIAL SHOWN IN FIGURE 1 AFTER KILN DRYING.

The checks have closed up, but the injury remains.



BADLY HONEYCOMBED OAK STOCK.

Result of too severe casehardening in drying.



CASEHARDENING EVIDENCED BY CUPPING OF THE BOARDS WHEN SAWED THROUGH PARALLEL TO THE SURFACE.

In Nos. 4, 5, 6 the stresses have been neutralized by steaming 36 minutes. In No. 7 the stresses were reversed by steaming 3 hours.

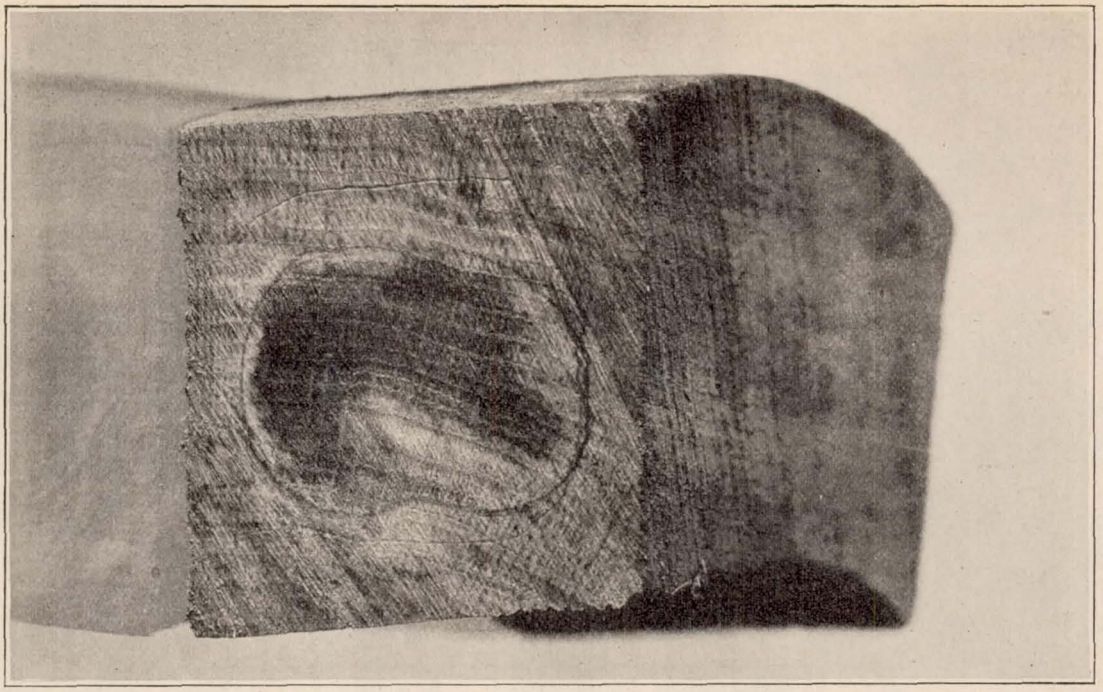


FIG. 1.—PARTIALLY DRIED WOOD WITH AN AREA OF FREE WATER REMAINING IN THE CENTER.
This block is in the first stages of casehardening. 3½ by 3½ inch oak wheel rim.

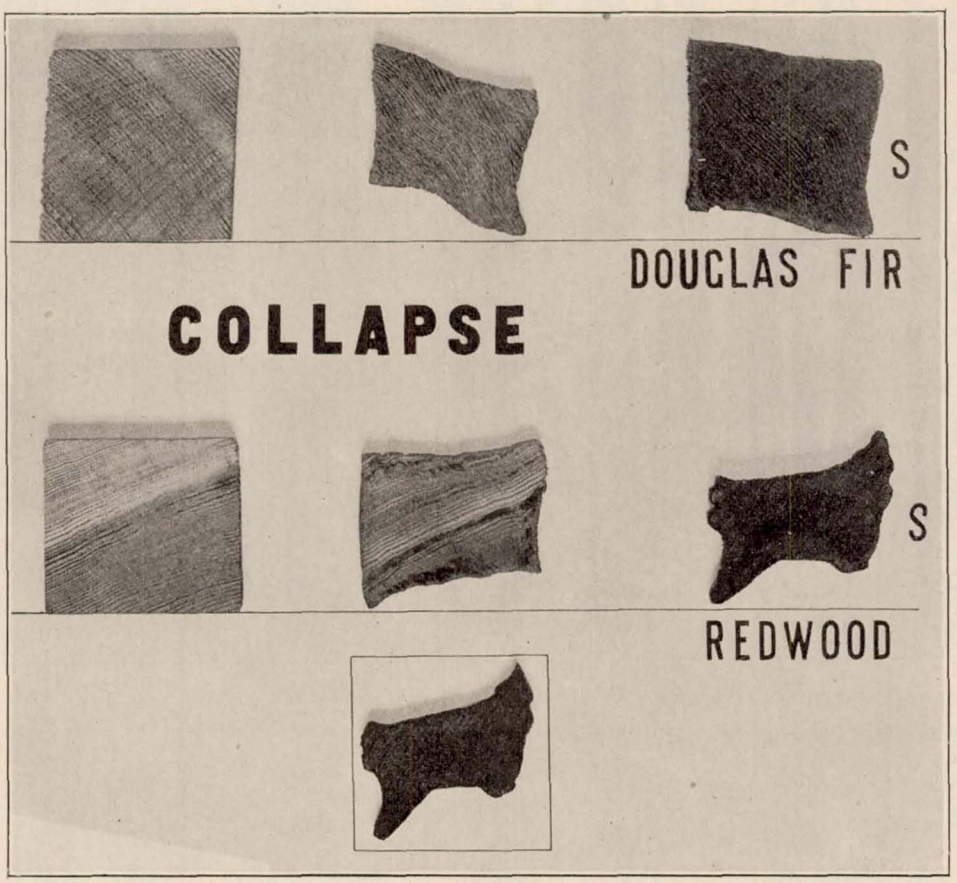


FIG. 2.—EXTREME CASE OF COLLAPSE IN 2 BY 2 INCH STICKS OF DOUGLAS FIR AND REDWOOD, PRODUCED BY HIGH TEMPERATURE WHILE MOIST.

There is no positive means of determining whether a piece of wood has been kiln dried or air dried, if the drying has been properly done, except where the temperatures used have been sufficiently high to harden the resins or gums or to discolor the wood. However, the outer layer of kiln-dried wood only a few days out of the kiln is apt to be considerably drier than the inside, whereas air-dried wood will generally be of uniform moisture content because it has had plenty of time for the moisture to equalize, or it may be even drier in the center than on the surface. But after the kiln-dried wood has been allowed to stand for several weeks, its moisture may become evenly distributed.

EXACTING REQUIREMENTS OF AIRPLANE STOCK.

For ordinary commercial purposes a reduction in strength of 15 or 20 per cent below the standard is of little or no importance in comparison with honey-combing, checking, and case-hardening, which, in the order named, are the most serious injuries likely to occur. Collapse, warping, and loosening of knots are also of importance, but are not likely to give trouble in any treatment which does not produce the first-named injuries. As these conditions are all visible to the eye, it is comparatively easy to adjust the drying operation until they are eliminated. Moreover, in most cases a slight checking, particularly when these checks finally close up again, is not considered detrimental, and for some purposes quite severe casehardening is not especially objectionable. Unequal moisture distribution, however, is always bad, except for the very roughest kind of work. Collapse, while quite common, does not occur in sufficient quantity to cause trouble, and warping is usually avoidable by proper care in piling. Considerable leeway is therefore possible in ordinary commerical drying operations, which explains the wide differences in the methods used. Even so, however, enormous losses exist which might well be wholly avoided by more care and intelligence in the treatment and in the design of the kilns. Moreover, the more exacting the requirements of the product, as for the best cabinet work, tools, musical instruments, etc., the greater refinement is necessary in the drying process.

For airplanes, however, strength and toughness are the prime requirements, and these qualities can not be determined by visual inspection. This fact renders the drying of lumber for airplanes a much more difficult and refined operation than for most other purposes. Actual mechanical tests are the only means of determining with any degree of certainty whether the material comes up to the standard. Since the dry kiln operator can not be guided by the appearance of the material, it is necessary to follow quite strictly certain prescribed specifications as to the drying operations. Different species require different treatments, as some are injured by conditions which are not harmful to others.

RELATION BETWEEN STRENGTH AND DRYNESS.

Dry wood is naturally very much stronger than wet. The crushing strength of green or wet spruce is increased *over fourfold* merely by drying.[1] It follows that the question what effect any particular process of drying has had upon the strength is necessarily a comparative one. From the mere fact that it has been dried, the wood has presumably been made stronger; the question is to what extent, or in other words whether the maximum of strength has been obtained. The answer to such a question can only be given through a comparison with some other drying process assumed as a standard. In making such a comparison the degree of dryness obtained must also be taken into account, since the strength increases progressively with reduction in the moisture content. For example, air-dried material may be taken as a standard. In that case the comparison would be made between kiln-dried material and air-dried wood of the same moisture content.

To make this matter clear and to facilitate further discussion of the general subject it is necessary to have in mind the basic facts regarding the composition of wood and the manner in which it dries.

[1] Forest Service Bulletin 70, "The Effect of Moisture upon the Strength and Stiffness of Wood," by H. D. Tiemann, 1906. Forest Service Circular 108, "The Strength of Wood as Influenced by Moisture," by same author.

II. HOW WOOD DRIES.

THE COMPOSITION OF WOOD.

Wood is made up of minute cells, arranged somewhat as the cells in a honeycomb except that the cells in wood are very much longer in proportion to their width than in a honeycomb, and are not as uniform. In the "softwoods" (gymnosperms) the vertical cells are fairly uniform in shape and size; but in the "hardwoods" (angiosperms) they vary greatly, some being fifty times as wide as others, the wide ones being termed "vessels" or "pores," and the narrow ones "wood fibers." Interspersed between these vertical cells and fibers and lying in a horizontal radial direction are the medullary rays, appearing as the "silver grain" on quarter-sawed oak. The medullary rays are composed of short, blunt, thin-walled cells, similar to pith tissue, and are shaped like two-edged swords set edgewise.

Plate V is a cross section of a gymnosperm (*Picea rubens*), and Plate VI of an angiosperm (*Quercus rubra* or *borealis*), both magnified the same amount, 250 diameters.

The substance of which wood is composed is half as heavy again as water; its specific gravity is 1.56. It is organic and consequently very complex in structure. The cell walls are thought to be built up of small particles closely laid together, the interstices being capable of filling up with moisture. The foundation part of this substance is known as cellulose. With it is combined another material called lignin which adds to the strength of the cell walls and gives them a color.

MOISTURE AND ITS REMOVAL.

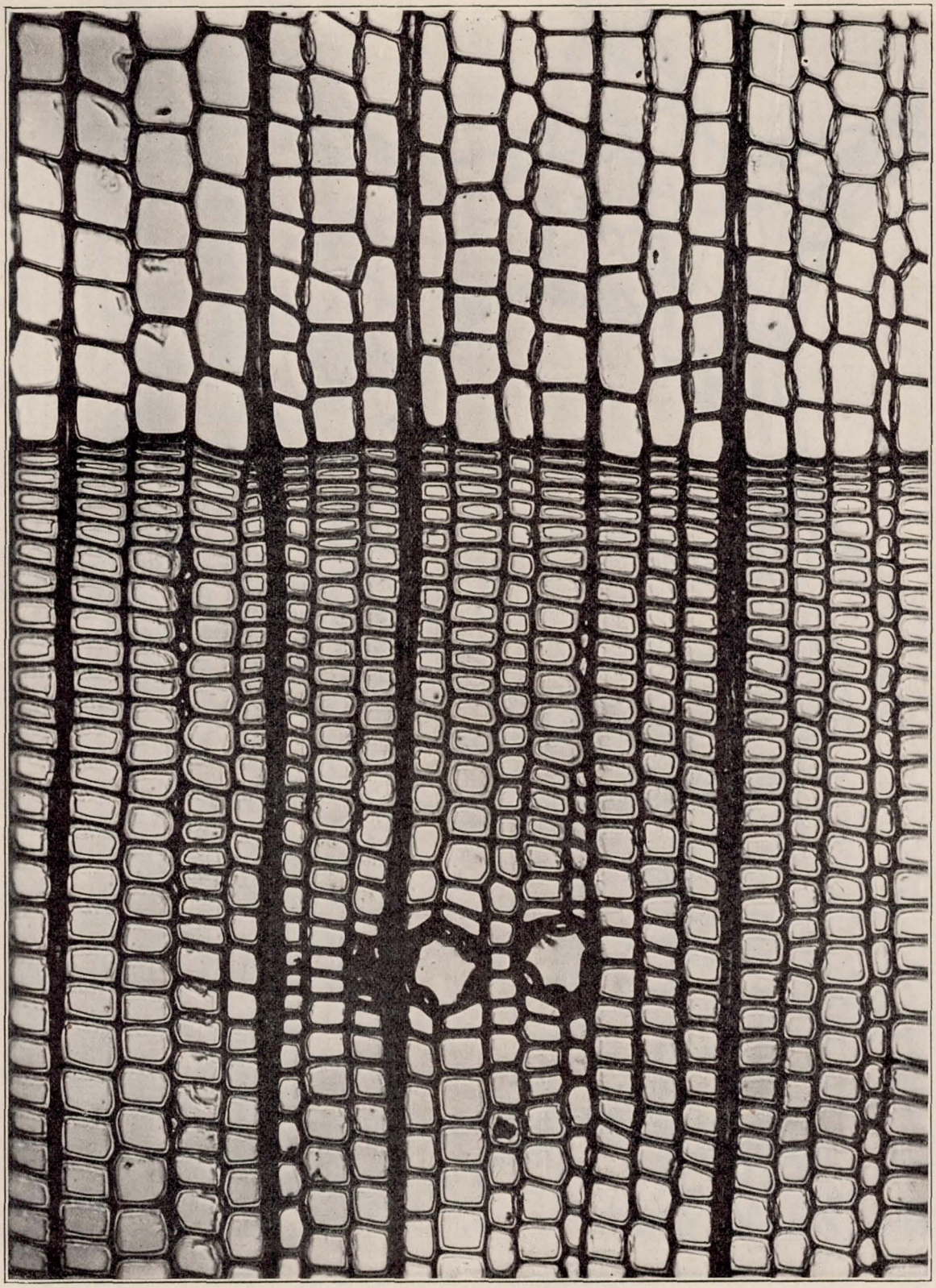
Wood in the living tree contains a great amount of moisture, varying from 30 per cent of the dry weight in the heartwood of some conifers, to over 200 per cent in some of the hardwoods. This moisture content must be greatly reduced before the wood is fit for use for most purposes.

In order to pass out from the interior of a board or timber the water must ordinarily pass transversely from cell to cell and evaporate from the surface. It is true that it can travel lengthwise very much more rapidly, as is evidenced by the end checking of lumber, but end drying can not be counted upon for removal of moisture from the center of a long stick. This process of transfusion from cell to cell is very slow, so that in ordinary air drying it takes 1-inch boards from six months to three years to reach 12 or 14 per cent moisture content, depending upon the kind of wood and the conditions under which it is dried.

In kiln drying, the process is greatly hastened by increasing the temperature and the air movement, thus increasing the rate of surface evaporation. This necessarily increases the differential in moisture content between the interior and the outer surface, since the rate of transfusion of moisture from the interior outward is partially proportional to this moisture difference. While the increased temperature presumably increases the transfusibility of the wood, it does not do so in proportion to the increased rate of surface evaporation. This necessary increase in the moisture difference brought about in order to hasten the drying is what causes the main difficulties in the kiln drying of woods.

These difficulties are due to the changes which take place in the wood itself in connection with the drying process after it has reached a certain point. Water exists in green wood in two forms—as liquid water contained in the cavities of the cells and pores and as "imbibed" or hygroscopic water intimately absorbed in the substance of which the wood is composed. The removal from the holes or pores of the free water will evidently have no effect upon the physical properties or shrinkage of the wood,[1] but as soon as any of the "imbibed" moisture is

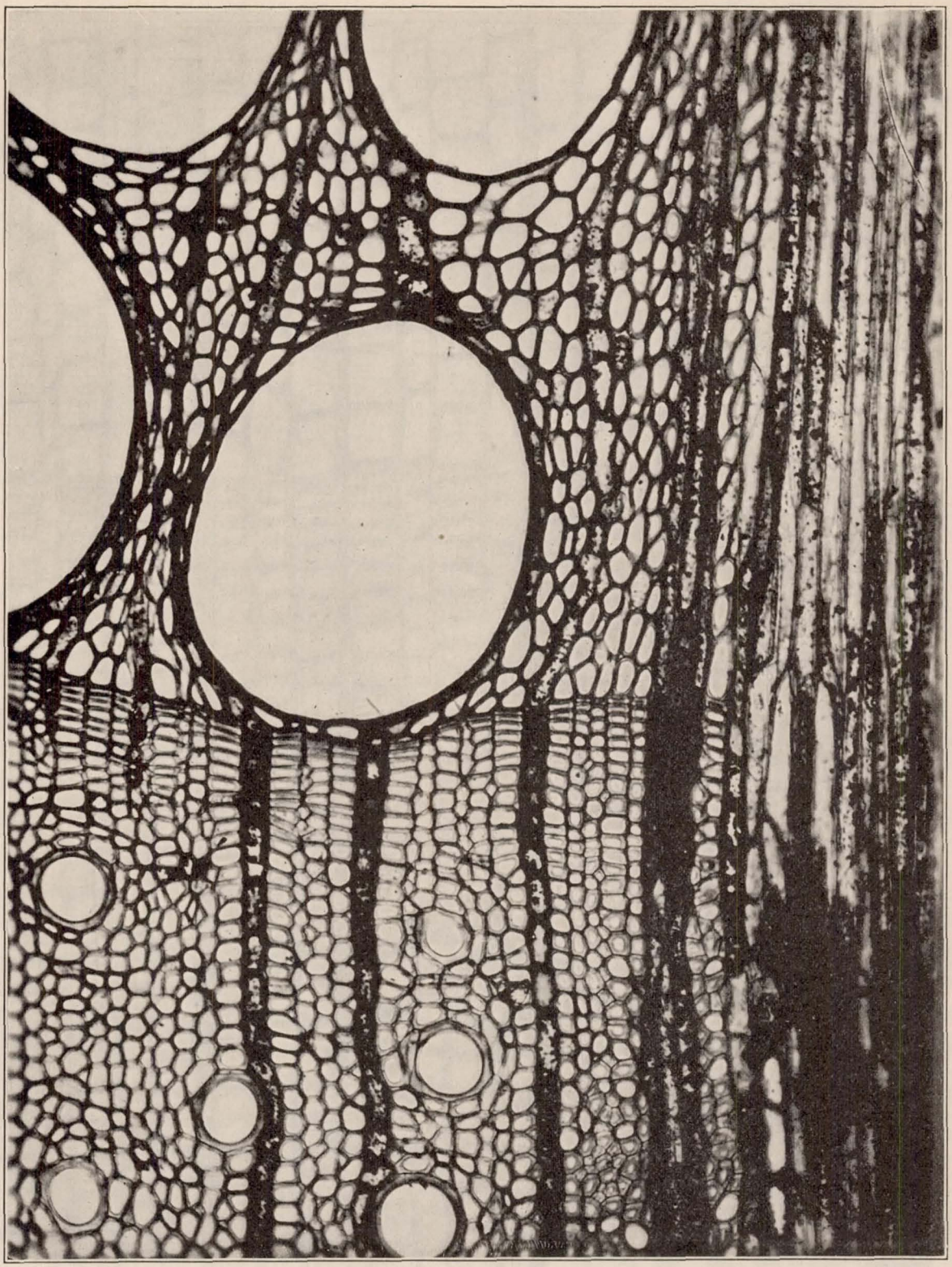
[1] An exception to this statement occurs in certain species, notably in western red cedar (*Thuja plicata*), in eucalyptus, and in redwood (*Sequoia sempervirens*), in which a collapse of the cell walls takes place in spots or bands during the evaporation of the free water. This collapse occurs only in excessively wet regions and when the wood is dried at too high a temperature. The explanation of this peculiar phenomenon appears to be that the cell walls, which are practically impervious to air while wet, but through which water may readily pass, become soft and plastic when heated. Under this condition those cells which are completely full of water to start with are subjected to an internal suction or tension produced by the depletion of the water in the cavity by its evaporation through the cell walls. The cells then collapse like rubber tubes, one layer after another.



MICROSCOPIC SECTION OF A GYMNOSPERM ("SOFTWOOD"), A PIECE OF RED SPRUCE (PICEA RUBENS) AT JUNCTION OF TWO ANNUAL RINGS.

The vertical lines are the medullary rays (radial). The center of the tree is below. Two resin ducts are visible in the summer wood. Magnified 250 diameters.

360–1



MICROSCOPIC SECTION OF AN ANGIOSPERM ("HARDWOOD"). A PIECE OF RED OAK (QUERCUS RUBRA OR BOREALIS) AT JUNCTION OF TWO ANNUAL RINGS.

The open vessels or "pores" are shown in the summer wood and a large medullary ray (radial) on the right. The center of the tree is below. Magnified 250 diameters.

360–2

removed from the cell walls shrinkage begins to take place and other changes occur. The strength also begins to increase at this time. The point where the cell walls or wood substance becomes saturated is called the *"fiber-saturation point,"* and is a significant point in the drying of wood. In some cases the free water can easily be removed by heating it above its boiling point, but in many cases this will injure the wood and in others the water contained in the cells themselves will not be forced out in this manner, only that from the open vessels or pores passing off in vapor. The chief difficulties, however, come in evaporating the free water where it has to be removed through its gradual transfusion through the cell walls instead of by boiling. The problem lies in the danger of drying the surface below its fiber-saturation point while free water still remains in the interior.

The fiber-saturation point lies between a moisture condition of 20 per cent and one of 35 per cent of the dry weight of the wood, depending upon the species.[1] In the living tree the wood is always above its fiber-saturation point.

PROPERTIES AND BEHAVIOR OF WOOD IN CONNECTION WITH MOISTURE REMOVAL.

GENERAL.

Different species vary greatly in the phenomena of drying. This is due to the fact that the properties which all possess in varying degree are combined in very different proportions. In consequence the response to a given set of conditions is of a widely diverse character.

One of these properties is the capacity to transfuse moisture. The rate of transfusion is very slow in some woods, as oak, and fairly rapid in others, as pine. The relation between rate of transfusion and temperature has already been mentioned in the preceding section. Transfusibility is, of course, the fundamental property of wood which makes drying possible, and the art of drying consists in so controlling transfusion, through control of the factors of temperature, humidity, and circulation on which its rate depends, that the changes in the other properties of wood which accompany drying are as favorable as possible.

Hygroscopicity is a property of wood closely related to transfusibility. It is the property by virtue of which wood substance absorbs or loses moisture in proportion to the relative humidity of the air, the rate varying slightly according to the temperature.

Change in color occurs in some species in drying. This is distinct from sap stain or colors caused by fungus or bacteria. It is notable in hard maple sapwood and in sugar pine. In the maple a moist, warm atmosphere is conducive to this coloration.

Under moist conditions combined with high temperature the wood substance becomes soft and plastic, while, on the other hand, as the moisture falls below the fiber-saturation point the wood substance hardens and stiffens. The effect of temperature upon plasticity varies greatly with different species, some, as, for example, western red cedar, redwood, oak, and eucalyptus, becoming excessively soft, even at temperatures as low as 150° or 170° F.

Tenacity, or cohesion between the fibers, easily breaks down with increase in temperature in such woods as western larch and the southern swamp oaks, thus permitting internal stresses to cause checking with great readiness.

Brittleness is produced by excessive drying.

Strength in wood is, of course, a very complex matter. It can not be discussed at length here. It is not a single property, nor even strictly speaking a group of properties, but is of various kinds, each kind being the result of more fundamental properties of the wood substance and of its condition with respect to such matters as internal stresses, checks, and other defects. The subject of the strength of woods for airplane stock is covered by another contribution to this series of monographs, entitled "Effect of Kiln Drying on the Strength of Airplane Woods." Among the phenomena which attend the drying of wood are two of such fundamental importance as to require further consideration. They are not independent, for the second is largely an effect of the first, but must be discussed independently. Both affect the strength as well as the form of the wood. They are shrinkage and casehardening.

[1] See Forest Service Circular 108, "The Strength of Wood as Influenced by Moisture."

SHRINKAGE.

It was previously stated that shrinkage does not take place until removal of the "imbibed" water from the cell walls begins. To this statement certain species of eucalyptus, oak, and probably other woods appear to present an exception in that shrinkage begins at a moisture condition of from 80 to 90 per cent of the dry weight. It is probable that this apparent shrinkage may in reality be a form of collapse.

Wood shrinks differently in different directions—as a rule it may be considered to shrink twice as much circumferentially as it does radially, and about one-fiftieth as much longitudinally, although this also varies in different species. Shrinkage continues until the substance is perfectly dry ("oven dry"), and it begins to swell again by absorption of moisture as soon as it is exposed to moist air. Alternate shrinking and swelling is inevitable with changes in the relative humidity of the surrounding air. This causes the so-called "working" of the wood. Different species vary greatly in this respect.

Wood shrinks more when dried slowly under moist conditions, especially at high temperature, than when dried rapidly.[1]

CASEHARDENING.

Casehardening is a somewhat ambiguous term as commonly used. It signifies in general a hardened case on the outside of the wood. In metal tempering the same word denotes the condition produced when the outer surface of an iron casting is changed to steel by heat treatment which removes part of its carbon. Doubtless the apparent analogy led to application of the word to conditions developed by heat treatment of wood. The analogy, however, is not a very good one and should not be followed too closely.

In seasoning wood a condition often arises in which the outer portion has become dry and hard, while the inner portion remains wet and loses moisture so slowly that drying seems almost at a standstill. This condition is due to the fact that the outer portion dried out faster than transfusion from the interior could take place, with the eventual result that the wood substance has become hardened and has largely lost its capacity to transfuse moisture. Because of the hygroscopicity of wood, however, the outer portion may in time, under favorable conditions, take up moisture again until a condition favorable to transfusion is again established, and drying may proceed at the normal rate. By steaming casehardened wood in this condition the fibers can be very quickly softened so that the normal seasoning process can be resumed.

But casehardening involves other factors. As the wood dries it also shrinks. If the outer and inner portions of a stick of wood dry unequally, there arises presently a condition in which unequal stresses have been set up. Such stresses are manifested by a tendency to deformation if the wood is cut in the manner presently to be described. From the standpoint of successful conditioning of wood in a dry kiln the most important aspect of casehardening is that which has to do with the unequal stresses which are brought about through unequal rates of shrinkage between the outer and inner portions as moisture is removed.

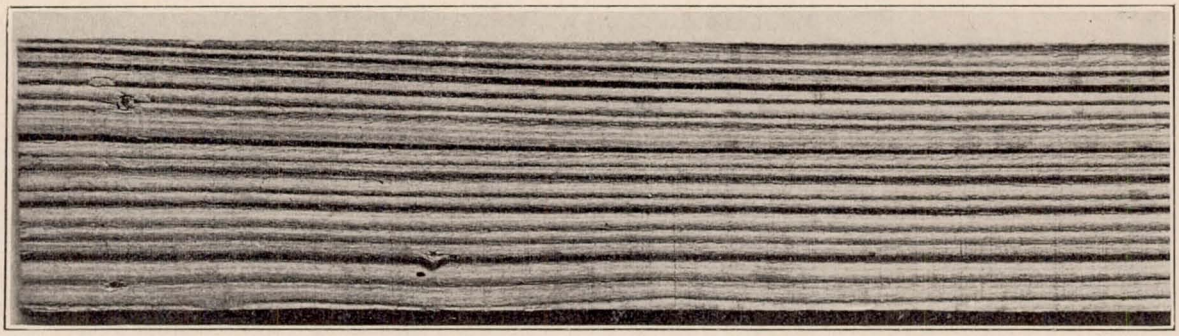
These stresses begin to be exerted as soon as a portion of the wood dries below its fiber saturation point. Since it is impossible, practically speaking, to season the wood rapidly without bringing about a condition in which unequal shrinkage takes place, a certain measure of casehardening may be said to be inevitable in kiln drying. Such stresses do not occur, however, to any appreciable amount when wood is very gradually seasoned, as in air drying under damp conditions.

But to understand fully the phenomena of casehardening account must be taken of still another factor. As soon as the moisture content of wood passes the fiber saturation point it begins not only to shrink but also to harden. The result is to set up a condition in which the wood has partially lost its capacity to shrink. It has become more rigid. This may or may not result in establishing what may be called a permanent differential of shrinkages between the outer and inner portions of the wood—that is, a condition in which one portion is always prevented

[1] Probably this is a secondary result dependent upon the factors of casehardening and collapse.

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PLATE VII.



"WASHBOARDING" IN AN INCH BOARD OF BLUE GUM (EUCALYPTUS GLOBULUS) DUE TO THE ALTERNATIVE COLLAPSE OF THE ANNUAL RINGS.

This board was perfectly flat when placed in the kiln, as is evidenced by the band-saw marks running across the surface

by another portion from shrinking as much as it would if free from a counteracting force. If such a permanent differential is not established, the casehardening will be temporary; if it is established, the casehardening will be permanent.

Four variable factors, then, are present in casehardening, and affect the result, namely, moisture content of the wood, degree of shrinkage, internal stress, and the period at which the fibers become hardened or set. These factors are partly dependent one upon the other. Temperature is still another factor, but may be treated as an independent variable.

OTHER EFFECTS OF DRYING.

Warping results from unequal shrinkage or from a warped direction of the fibers. Cupping is due to unequal shrinkage of slab cut boards radially and circumferentially and is simply explained by geometrical relations.

Washboarding is due to unequal shrinkage of adjacent layers of the annual rings of wood, and appears on radially sawed (quarter sawed) lumber. (See Pl. VII.)

Collapse of the cells may occur in some species while the wood is hot and moist. This collapse is distinct from the shrinkage which takes place in the wood substance and is due to a different cause.

Checking and honeycombing are caused by unequal shrinkage, crooked grain, and casehardening.

III. THE ART OF CORRECT KILN DRYING.

Were it not for the unequal shrinkage and the slow rate of transfusion of the moisture from cell to cell, the drying of lumber would present no more difficulty than the drying of wet cloth or clay. The problem of kiln drying wood would be merely one of conducting the requisite amount of heat to the material to supply that required for vaporization, which at 163° F. is 1,000 British thermal units of latent heat per pound of water, plus a small additional amount (about 30 B. t. u. per pound of dry wood)[1] required to overcome the attraction of the hygroscopic material for the moisture. By use of a temperature higher than the boiling point corresponding to the given pressure, the moisture would pass off directly in proportion to the quantity of heat supplied. But the process is more complex in the case of wood.

EFFECT OF THE SURROUNDING CONDITIONS ON DRYING.

There are just three conditions which it is essential to control properly for correct drying: (1) Circulation of the air, (2) humidity, and (3) temperature; and it is important that these conditions be uniform throughout the kiln.

EFFECT OF CIRCULATION.

Unless the circulation is sufficient to convey throughout the pile of lumber the heat necessary for evaporating the moisture, and also sufficient to carry away the vapor, uniform drying is impossible. The humidity of the air throughout the pile is dependent upon the circulation For drying an isolated single stick of lumber circulation is unimportant, since the stick would receive heat on all sides by convection or radiation and the moist vapor would pass away by diffusion; but for a pile of lumber of any considerable size, a decided movement of the air through the pile is necessary.

Since evaporation involves a consumption of heat and its transformation into latent heat, and at the same time an increase in the humidity of the air immediately surrounding the object, it is evident that drying in all parts of a pile of lumber can not take place under the same temperature and humidity condition at one and the same time. Where the air passes through a pile in a definite direction the temperature is highest and humidity the least at the place where the air enters the pile, and the temperature is lowest and the air dampest where it leaves the pile. Consequently drying takes place progressively through the pile in the direction of the air circulation. The more rapid the circulation the more uniform will be the conditions through the pile. Something of this same condition exists whether the circulation is in a definite direction or is irregular, only irregular circulation does not lend itself to analysis and variations are more irregular and usually much greater in amount. Variations of from 30° to 50° F. are not uncommon when circulation is indefinite, and humidity variations are from very dry to saturation.

EFFECT OF HUMIDITY.

If it were merely a question of evaporating moisture the most economical drying system would be one in which the air entered the pile of lumber in the driest attainable cond tion and left the pile in a saturated condition.[2] But the more important part played by the humidity is its physical effect upon the wood. There is a natural balance between the hygroscopic moisture assumed by wood and the relative humidity of the surrounding air at a given temperature.[3] For the avoidance of checking and casehardening it is essential that the surface of the piece of wood be kept comparatively moist while the water is passing from the center to the surface. In other words, the surface must not dry at a more rapid rate than the moisture transfuses

[1] Unpublished report, Forest Products Laboratory, by Frederick Dunlap.

[2] See Department of Agriculture (Forest Service) Bulletin 509, "The Theory of Drying," etc., by H. D. Tiemann, pp. 22 and 23.

[3] "The Kiln Drying of Lumber," by H. D. Tiemann, pp. 103 to 105 and 263.

from the center of the stick to the surface. This is brought about by retaining a definite amount of humidity in the air during the drying operation. This fact is of special significance in the drying of green lumber, where the aim is to keep the surface *as near its fiber saturation point as possible until all the free water has evaporated from the center* after which the moisture condition of the surface can be gradually reduced by lowering the humidity. Humidity is also of importance in establishing the final moisture content before removal from the kiln. As there is a definite relation between relative humidity and the percentage of moisture which the wood will retain, it is evident that by regulating the final humidity in the kiln, overdrying may be prevented.

EFFECT OF TEMPERATURE.

The temperature influences both the mechanical efficiency of the operation and the physical effect upon the wood. In general, the higher the temperature the more efficient is the operation; but this is completely and definitely limited by the effect upon the wood. The temperature at which drying may be safely conducted without injury to the material varies greatly with different species. For example, oak must be dried to start with at not over 110° F., while Douglas fir for commercial purposes (not for airplanes) will stand over 225° F. without appreciable injury.

The effect of high temperature is (1) to soften the fibres; (2) to reduce their cohesion in tension, so that slight stresses will cause separations or checking and honey-combing; (3) to affect permanently the strength if certain limits are exceeded; (4) to tend to increase the shrinkage and produce collapse; and (5) presumably to increase the rate of transfusion of the moisture through the wood. Chemical changes also occur and the hygroscopicity of the wood is reduced.

These different effects are produced proportionally very differently in different species, so that the resultant effect of a given temerature with one species may be altogether unlike that with another. Thus, high temperature greatly softens the fiber of oak but it reduces its cohesion in a greater proportion, so that checking is more liable to occur at high than at low temperatures. On the other hand, in most softwoods the cohesion is not reduced relatively to so great an extent, consequently they may be dried at higher temperatures, normally than oak and similar hardwoods.

On account of the softening of the fibers and the increased transfusion, casehardening is less at a high than at a low temperature if the drying rate is the same in both cases.

IV. DISCUSSION OF DRY KILNS AND MEANS OF CONTROLLING THE ESSENTIAL CONDITIONS.

A dry kiln is sometimes thought of as a hot box or baking oven, or as a certain shaped building; rightly, however, it should be considered as an apparatus for conditioning lumber by supplying certain definite requirements. The essential requirements are adequate and uniform circulation throughout the pile of lumber; control of humidity at all time; control of temperature; and ability to steam the lumber quickly and effectively whenever necessary for removal of casehardening and killing of mold. These essentials have already been discussed.

SYSTEMS OF KILN OPERATION.

There are two distinct ways of handling lumber in kilns. One way is to place the load in a chamber where it remains stationary throughout the operation, while the conditions of the drying medium are varied as drying progresses. This is the "compartment" or "charge" system of handling the lumber.

The other way is to run the lumber on a wheeled truck into one end of a long chamber and gradually shove it along toward the other end, where it is taken out when the drying is completed. An attempt is made to keep the end of the kiln where the lumber enters moist, and the other end dry. This is known as the "progressive" system of operation, and is one commonly used in large operations. It is the less satisfactory of the two, however, where careful drying is required, since the conditions can not be so well regulated and are apt to change with every change of wind and with every new load of lumber introduced. It is not to be recommended for use with airplane stock.

The compartment system can be arranged so that it will require no more kiln space or handling of the lumber than the progressive system; it does, however, require more intelligent operation, since the conditions in the kiln must be continually altered according to the progress of the drying. Either of these two systems may be used with almost any kind of dry kiln.

As a rule the progressive system employs a simple ventilated kiln such that the air enters at the dry end (where the lumber is taken out) through ducts placed in the bottom beneath the heating pipes, is heated as it rises between the pipes, thence passes through the lumber in a horizontal direction, opposite to that in which the lumber is being moved, and is finally discharged through chimneys at the damp end. The heating pipes usually extend only about two-thirds the length of the kiln from the dry end. Such kilns vary in length from about 60 to 150 feet and in width from 18 to 24 feet, and are about 14 to 16 feet in height.

METHODS OF SECURING CIRCULATION.

Pressure and superheated steam treatments are not suitable for airplane material; and the vacuum treatment, though suitable, is hardly practicable. It will, therefore, suffice to consider only atmospheric pressure treatments.

In general the circulation is produced in three ways:

(1) By external draught or ventilation, where the air is taken in from the outside, conditioned, passed through the kiln, and allowed to escape to the outside again.

(2) By recirculating the air within the kiln itself and removing the excess moisture by condensation.

(3) By forcing external air through the lumber by means of a fan or blower.

Combinations of these methods may also be used.

So long as the fundamental requirements already specified are definitely secured, any one of these systems may be used for drying airplane lumber, but they are not all equally satisfactory. The mechanical features having to do with the operation of the kiln, the accuracy and certainty of control of the conditions, and the amount and uniformity of the circulation differ greatly in their effectiveness in different types.

VENTILATED KILNS.

In a purely ventilated kiln the circulation of air is usually either entirely too sluggish for drying green wood if the humidity is uniformly distributed, or if the draft is sufficient for drying the green wood the changes in the humidity are excessive. Usually the deficiency of the humidity in the air as it enters the lumber has to be made up by injecting live steam into the current of incoming air. This arrangement is often precarious. Changes in temperature of the outside air greatly affect the internal conditions. In general, ventilated kilns are not suitable for drying green airplane woods. They are much more suitable for drying air-dried lumber than green. It is difficult to maintain control of conditions in this type of kiln. Nevertheless, for certain kinds of drying such as 1-inch lumber of easily dried species a ventilated progressive kiln is probably the simplest, most easily operated, and most economical design possible.

RECIRCULATION KILNS.

In the ordinary type of recirculation kiln, pipe condensers are commonly used to remove the excess moisture from the air. Unless there is some additional means of increasing the circulation of the air, however, its natural movement is apt to be too slow for the rapid drying of green lumber except at high temperatures and low humidities, which are prohibitive for airplane stock. In the Forest Service humidity-regulated water-spray kiln,[1] which belongs to the internal-circulation class, the circulation is greatly accelerated by means of sprays of water uniformly spaced the entire length of the kiln and placed in narrow chambers, one on either side, or in a single chamber through the middle. The water sprays at the same time control the humidity of the air. This kiln has been largely used for drying airplane stock. Another means of producing the needed circulation is by placing fans directly in the kiln itself, and thus forcing the air through the lumber. The main difficulty of this plan is so to arrange the fans that a uniform circulation is produced in all parts. Humidity control is also somewhat difficult of accomplishment, as it depends upon leakages through the walls, canvas curtains or ventilators, together with the injection of live steam through perforated steam pipes. This type of kiln has been very successfully used in drying green airplane stock.

BLOWER KILNS.

In the third class a blower or fan is used to force in new air. This is usually placed outside of the kiln proper, and air is sucked out and returned to the drying chamber through ducts. Ventilation is secured by admitting more or less fresh air and allowing some of the return air to escape. Accurate control of conditions is usually difficult to maintain, since the slightest change in adjustments of the steam jets or of the dampers very quickly and progressively alters the conditions in the kiln. Such an arrangement is in what might be considered unstable equilibrium. Where a battery of kilns is used, a separate blower is required for each kiln, otherwise they can not be operated as independent units.

CIRCULATION CONTROL.

In the design of any kiln and method of piling it should always be borne in mind that the load of lumber itself, particularly when first introduced, acts as a powerful condenser. The evaporation is of itself a cooling operation, and calculation shows that the effect of evaporation is to increase the density of the humid air in spite of the fact that more vapor has been thereby added.[2] This means that there is a natural tendency of the air to descend as it passes through the lumber, particularly when rapid drying is taking place. The arrangement of the pile of lumber and the kiln, therefore, should be such as *not to oppose* but *to assist the natural gravity tendency.* Success or failure sometimes hinge on this point. Extensive observations under all kinds of conditions and in all kinds of kilns have shown that this theory of the downward tendency of the air through the pile is the correct principle.

[1] See Appendix III.

[2] See Bulletin 509, "The Theory of Kiln Drying," etc., p. 27.

HUMIDITY CONTROL AND STABLE EQUILIBRIUM.

Humidity control is brought about in various ways, and its accomplishment is the most difficult problem in regulating the dry-kiln operation. In ventilated kilns the humidity is usually varied by the amount the dampers are opened, the moisture added to the air being that evaporated from the lumber. Very often steam jets are used where it is necessary to add humidity to the air; or vessels of heated water are used. In condenser kilns the temperature of the pipe condenser is altered, to change the humidity, by altering the flow of water through the pipes. Steam jets are also used to add humidity as required. In the blower kilns similar means are employed and, in addition, the dampers admitting fresh air are adjusted. In the Forest Service water-spray kiln the humidity is automatically controlled by regulating the temperature of the spray water. Hot water in the sprays gives a high humidity, while cold water acts as a condenser and gives a low humidity. The control is very direct and the water acts in addition as a stabilizer, preventing any sudden changes of conditions. The kiln is in a condition of what might be termed stable equilibrium.

TEMPERATURE CONTROL.

This is the simplest problem with which the dry-kiln engineer has to deal in the design of a dry kiln. When conditions are fairly uniform, the temperature may be approximately regulated by turning on a greater or less number of steam pipes, if the piping system is installed in independent units. Wherever high-pressure steam is available, temperature may be largely controlled by means of a pressure-reducing valve. Both systems combined increase the range obtainable. Very steady temperatures may be thus maintained, but the difficulty is that when the temperature begins to change it may continue to rise or fall progressively, and if not closely watched will soon pass the desired limits. Throttling steam valves by hand is not recommended.

The safest method is to use one of the many good makes of thermostat, having a control bulb which may be placed anywhere desired in the kiln, and connected to the operating mechanism by a long, flexible tube. Any degree of accuracy of temperature control desired can be secured by the use of a suitable instrument of this kind. Some are made to act directly upon the steam valve by the expansion of vapor contained in the bulb, or by the expansion of a liquid. Others are made to operate through an auxiliary or relay system, the motive power of which consists of air pressure or water pressure, which in turn operates a motor valve on the steam line.

For the most delicate control the air-pressure relay system has proved the best, while for certainty action and simplicity one of the direct-acting systems is to be recommended. Any one of these systems is satisfactory, and no kiln for accurate drying should be operated without some form of thermostat.

Heating systems as a rule consist of a series of ordinary iron pipes placed near the floor of the kiln. In blower kilns the air is often heated either by pipes or by furnace before it is forced into the kiln. Sometimes ordinary radiators are used. Whatever the heater, the main thing is to have it properly controlled and the heat uniformly distributed and constantly supplied.

A return bend system of piping has proved the most satisfactory for compartment kilns, as it gives uniform heating at both ends of the steam coil. The header system, while more commonly used, is apt to heat one end more than the other. This is particularly so when low-pressure steam is used and in high-pressure systems when a thermostat is placed on the feed line. If the traps fail to operate properly or the pipes become air bound, the drainage end is certain to be colder than the supply end. The return bend system, made up of several separately controlled coils of pipes, is strongly recommended. One-inch piping is very commonly used for dry kilns and often 1¼-inch and occasionally 1½-inch piping. For low-pressure steam the larger pipe is preferable.

Temperature control is especially important in drying airplane stock, since if certain limits are exceeded the strength and toughness are affected.

V. DETERMINATION OF CONDITIONS IN KILNS.

IMPORTANCE OF ACCURATE KNOWLEDGE OF CONDITIONS FOR AIRPLANE STOCK.

For airplanes, strength and toughness are the prime requirements, and these qualities can not be determined by visual inspection. Actual mechanical tests are the only means of determining with any degree of certainty whether the material comes up to the standard. These tests in order to be determinative must be made upon matched material from the same sticks, and the testing of the material and analysis of results is extremely complicated and difficult. How these tests have been made for a number of species at the Forest Products Laboratory, and the results secured, are set forth at length in Report No. 68.

The fact that strength conditions can not be satisfactorily determined by visual inspection alone when airplane material is concerned renders the drying of such material a much more difficult and refined operation than that of drying lumber for most other purposes, and necessitates that the operator follow strictly certain prescribed specifications.

USE OF THERMOMETERS AND HYGROMETERS.

A single thermometer reading should never be relied upon, and it may be necessary to place thermometers in a dozen or more different places in the kiln and take readings of them all frequently throughout the entire run until the proper place for taking the controlling conditions has been determined upon. All thermometers should be checked together occasionally by placing their bulbs together and surrounding the set of bulbs with some insulating material, such as a dry woolen cloth. The kiln should be controlled not by an average of the various readings, but according to the conditions at some point or points carefully selected, after a study of all the readings. The success of the run may depend largely upon the judgment used in choosing the proper places for measuring the conditions. If the readings at the different positions in the kiln appear to be inconsistent, sets of readings should be taken at short intervals, both at a time when the temperature is rising and again when it is falling, and the thermometers moved about until consistent readings are obtainable. It is not always easy to predict where the hottest portion of the kiln will be, and even when this is found it may not necessarily correspond to the air temperature entering the pile of lumber. Furthermore, the air may enter the lumber at one place during the beginning of the run and at another place at the finish, in which case the place for measuring conditions controlling the run must be shifted accordingly. Or there may be no apparent place which might be considered as "entering air". In this case the hottest portion of the pile should be chosen as supplying the condition for controlling the run.

Since it is assumed that material from any portion of the pile is likely to be used in manufacture, it is necessary that no portion of the pile be subjected to conditions more severe than those specified. Hence it is necessary to govern the entire kiln by the most severe conditions to which any portion of the pile may be subjected, irrespective of whether other portions are drying too slowly or not.

In dry kilns where the circulation of the air is in a known direction, the proper place at which to measure temperatures and humidities for controlling the drying run is where the air first enters the pile of lumber. In the water-spray kiln this place is in the warm air flue (opposite the spray chamber side of the pile), about half way up the pile and about the middle of the flue. Ordinarily a thermometer or hygrometer so placed will not need to be shielded from radiation.

RECORDING THERMOMETERS.

While not essential, recording thermometers are very useful not only in furnishing a permanent record of the run but also in indicating how to control the conditions. While optical readings of glass thermometers give only points in the curve of operation, the recorder gives a continuous record; and it is very easy to learn from the recorder whether conditions are steady, variable, rising, or falling.

Unfortunately, recording thermometers have not proved altogether reliable and they should not be wholly depended upon. Standard glass thermometers should always be used in the kiln in addition to the recorders. The recorders should also be checked frequently with a standard glass thermometer.

The recorders most useful in dry-kiln work are those in which the measuring bulb is connected with the recording instrument by a long, flexible capillary tube filled with a fluid. The bulb is placed at the point where the temperature is to be measured, and the recording instrument in a convenient room, which should be at a lower temperature than the bulb.

These instruments are of four types, according to whether the fluid in the bulb and tube is (1), mercury, (2) some nonvolatile liquid, (3) gas, or (4) a volatile liquid which produces the pressure on the operating spring through vaporization of a portion of the liquid.

In the first three types it is important that the spring in the recording case and that portion of the tube not subjected to the temperature to be measured be kept at a fairly uniform temperature, since any changes in the temperature of any portion of the fluid contents will affect its pressure according to the relative volume affected. Compensating devices are usually attached to such instruments supposed to correct for such changes, but experience shows that they do not always compensate with complete satisfaction, especially in the case of the liquid-filled instruments.

The only instrument which is not subject to changes in temperature of any part of the vessel is one filled with a volatile liquid and its vapor. Since the action of this instrument is produced solely by the pressure of saturated vapor and not by the expansion of the liquid or gas, it is not affected by temperatures which are lower than the temperature of the bulb. Its action is the same as that of a steam pressure gauge; in fact, the thermometer is in reality nothing more than a saturate vapor pressure gauge; and since the pressure of saturate vapor is always the same at a given temperature, independent of the volume or of the lower temperature of the liquid, this form of thermometer is the most accurate and reliable if properly used. The main precaution is that no portion of the tube or the spring must be heated above the temperature of the bulb. The tube and spring will then be full of the liquid, and the vapor will be generated in the bulb in the presence of some of the liquid, which is always sufficient to fill part of the bulb as well as the tube and spring.

This form of instrument may be at once distinguished from the other three forms by the divisions on the dial, which in the others are uniformly spaced but in the vapor instrument widen out as the temperature increases. In one make a patented device is attached which comes into action at a prescribed temperature and narrows down the spacings.

In the gas-filled instrument it matters not at what height the recording dial is placed relative to the bulb; but in the liquid and vapor instruments the vertical height of the liquid column exerts a pressure, which requires a readjustment of the hands when this height is altered.

PLACEMENT OF RECORDING THERMOMETERS.

For the water-spray kiln the vapor form of instrument is recommended. Two separate bulbs operating on one dial are desirable, one to record the dew point, the other to record the entering air temperature. The dew-point bulb should be placed in the lower opening of one of the baffle boxes, on the spray-chamber side, but in such a manner that it does not receive the direct spray of water nor rest directly on the floor; and the tubing should extend through the spray chamber itself to the end of the kiln and pass directly out through the end wall. This is to insure that no portion of it becomes heated above the bulb temperature. The case also must be situated in a room which is cooler than the dew-point temperature to be measured. Care should be taken to see that the bulb is placed in a "live" part of the spray chamber and not where the conditions of spray or circulation are abnormal from any cause.

The bulb for measuring the temperature of the air entering the lumber (dry bulb) should be suspended in the warm air flue about half way to the top of the pile and midway across the flue, and the tubing should be carried horizontally on a level with the bulb through the flue to the end of the kiln and thence through the wall to the instrument. It must not pass near any hot pipes. So placed, the bulb need not be shielded from radiation. It is important that this bulb does not lie on line with the space between the ends of two piles, but it should come somewhere near in line with the middle of the pile. The same applies also to the dew-point bulb, since the circulation will be apt to be abnormal between the piles, and the true conditions of the air which enters and leaves the pile would not be correctly registered.

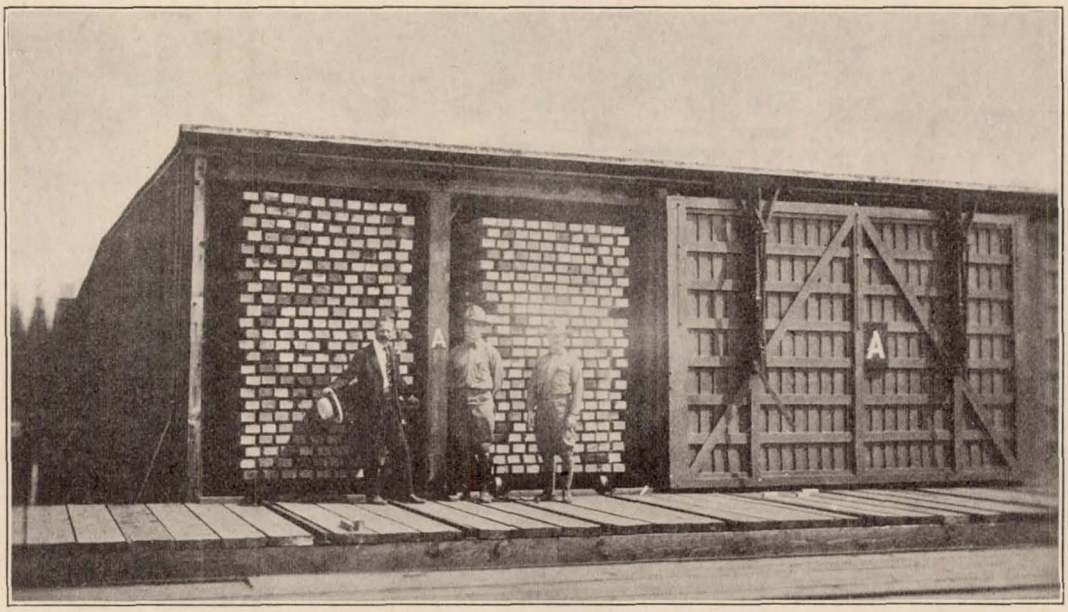


FIG. 1.—ONE OF THE 24 WATER SPRAY DRY KILNS AT THE SIGNAL CORPS CUT-UP MILL, VANCOUVER WASH., OPENED PREPARATORY TO UNLOADING; SHOWS METHOD OF PILING WING-BEAM STOCK.

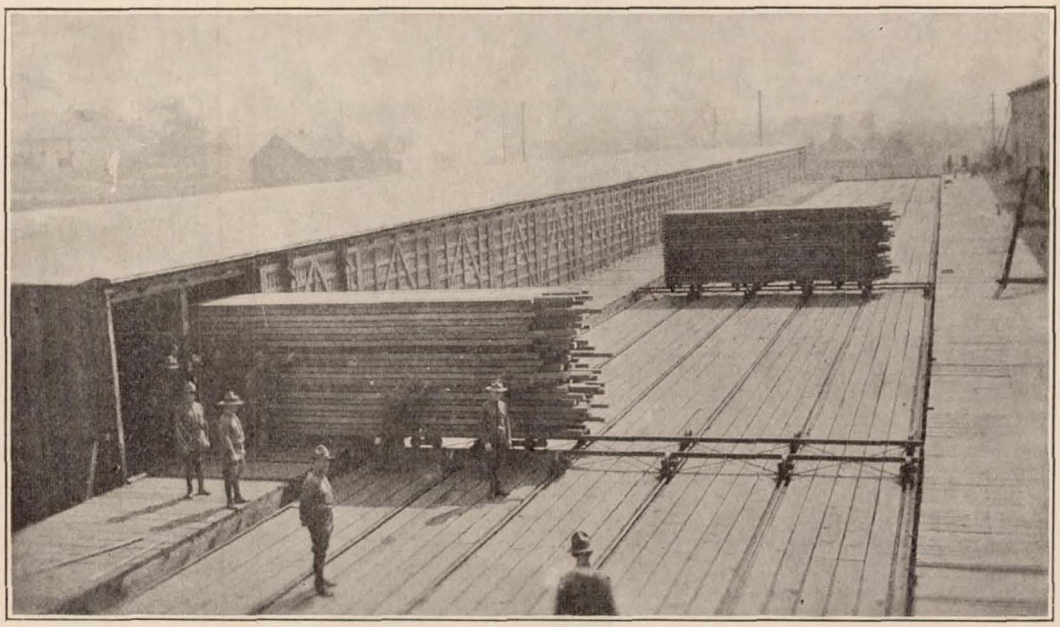


FIG. 2.—GENERAL VIEW OF THE BATTERY OF 24 WATER SPRAY DRY KILNS USED FOR KILN-DRYING WING-BEAM STOCK DURING THE WAR AT THE SIGNAL CORPS CUT-UP PLANT AT VANCOUVER, WASH.

VI. HOW TO CONDUCT THE DRYING OPERATION.

METHOD OF PILING.

In general lumber should be so piled as to afford free passage of the air throughout, and so that the air will pass through the pile and not around it. It is frequently advantageous to hang canvas curtains in such a manner as to prevent the air from short-circuiting the pile.

Remembering that the drying takes place progressively through the pile, it is evident that the pile should not be made too large, as otherwise what is gained in size will be lost in time of drying. This applies also to the question of how close together to place the sticks. If the pile is too crowded, the increased capacity will be lost in slowless of drying. Again, if the lumber is too openly piled the capacity of the kiln is unduly cut down without a compensating gain in time of drying. It is better to err on the side of too open rather than too close piling, since no harm will result other than loss in capacity, whereas too close piling may result in very uneven drying.

The greater the circulation in the kiln, the larger and closer may be the pile. For an ordinary condenser kiln without forced circulation it is generally desirable to allow about twice as much air space as solid lumber in the pile. Thus, for 3 by 4 inch wing-beam material 2-inch stickers and 2-inch spacings are preferable. Where high circulation is attainable this may be cut down to equal parts, or even to 6 parts solid to 5 parts open. Thus for 3 by 4 inch wing beams, 1 or 1¼ inch stickers with 1½ to 2 inch horizontal spacings may be used. For 1-inch boards 1-inch stickers should be used, when there is high circulation, and 1½-inch for low circulation.

In the water-spray kiln and in pipe condenser kilns the lumber should be run lengthwise of the kiln and the individual piles should not exceed 8 feet in height and 5 feet in width. An open flue of 18 inches should be left through the center of the kiln between the two 5-foot piles, and at least 12 inches between the lumber and the side walls.

A suitable method of piling wing-beam stock is illustrated in Plate VIII, which shows one of the kilns at the United States Signal Corps cut-up mill at Vancouver, Wash., opened for unloading. This kiln is loaded with 3 by 5 inch Douglas fir wing-beam stock.

Unless the drying takes place evenly from both surfaces of the boards there is a strong tendency for them to cup. Consequently the arrangement of the pile with respect to the movement of the air is of great importance from this point of view.

TESTS OF MATERIAL DURING AND AFTER DRYING.

For correct drying and the control of the whole operation it is essential to know currently the condition of the wood in various portions of the pile in regard to moisture, casehardening, and checking, as well as the temperatures, humidities, and air movements. Tests of the material must therefore be made as often as required. There are two means of acquiring this information; namely:

(1) By the direct-test method.
(2) By the sample-piece method.

The following tests are to be made:

(1) Average moisture.
(2) Moisture distribution.
(3) Casehardening.

DIRECT-TEST METHOD.

One means of ascertaining this information is to pull out sticks of the wood from different places periodically and to test them for moisture and casehardening. Such tests must be made at a considerable distance (2½ or 3 feet) from the ends of the sticks, as otherwise they are liable to give erroneous conclusions due to the ends of the sticks having dried very much faster than the centers. It is frequently difficult if not impossible, however, to pull out representative material from the piles during the progress of the drying, and another method must be resorted to.

SAMPLE-PIECE METHOD.

This method can be best applied by preparing suitable sample pieces beforehand and inserting them into suitable pockets left in the sides of the piles when the lumber is first loaded. The samples should be representative material, cut from near the center of the chosen sticks and not less than 2½ feet in length. They should include some of the wettest as well as the average material, otherwise the load is likely to be considered dry before the wettest pieces have reached the required dryness. A 1-inch moisture disk should be taken from either end of the sample at the time of its preparation and immediately weighed on a delicate balance. The sample also should be weighed within a few minutes of the disks. The ends of the samples should then be thoroughly coated with thick asphaltum varnish, or be dipped in melted rosin 100 parts, lampblack 7 parts. The samples are then ready to be placed in the load in the pockets left for them. When samples are thus in place they should lie in exactly the same

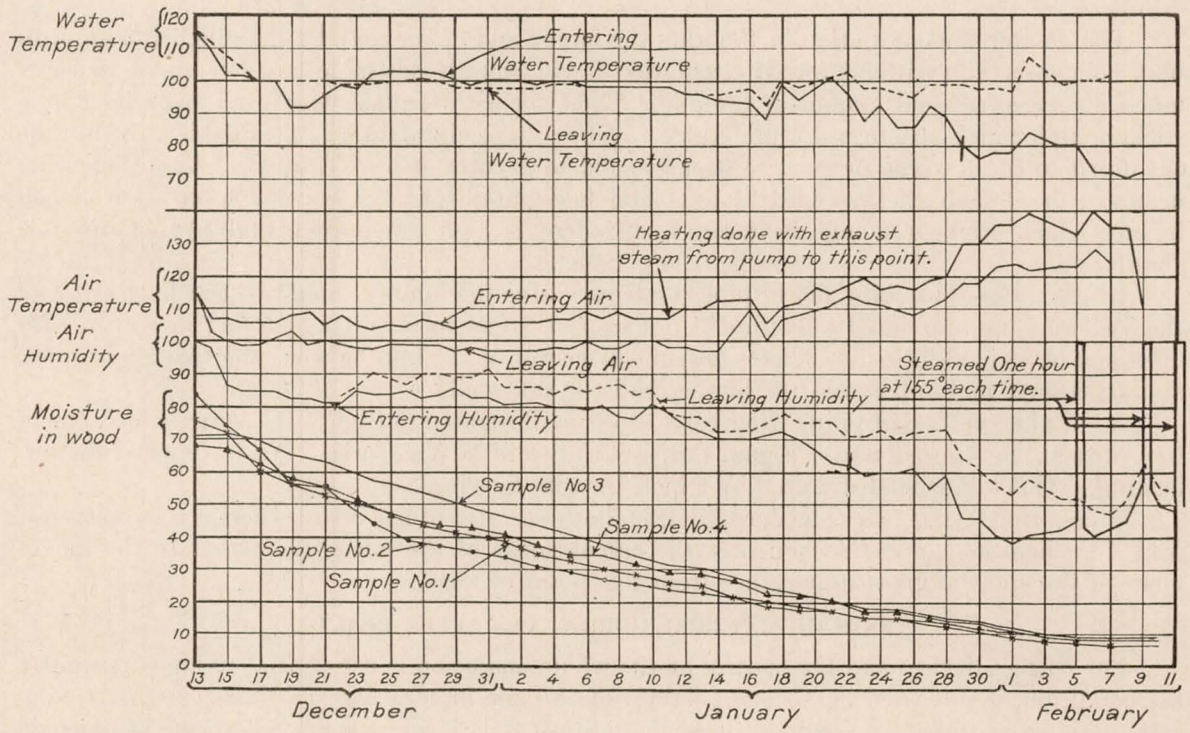
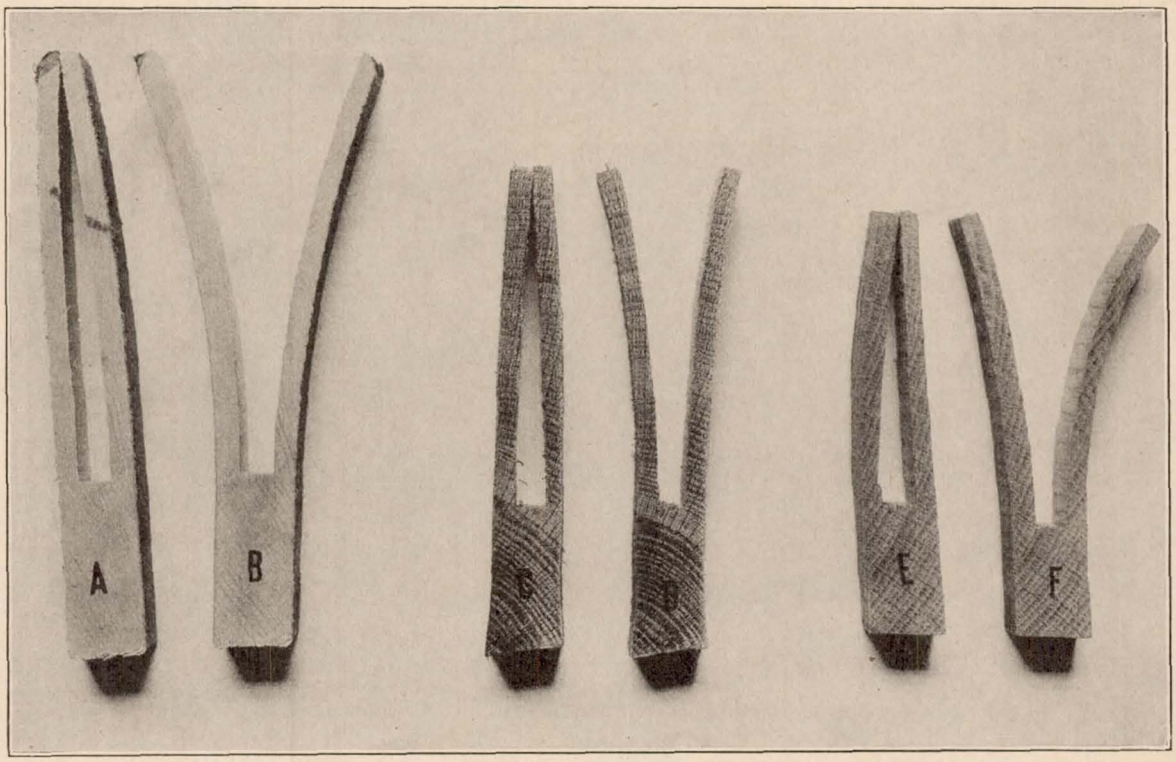


FIG. 1.—DRYING RECORD OF RED AND WHITE OAK PROPELLER STOCK, SHOWING METHOD OF PLOTTING DATA AND KEEPING TRACK OF CONDITIONS.

relative positions as the other sticks in the pile, the ends being pieced out by the ends of the sticks from which they were cut and they must be readily accessible so that they can be removed and replaced as often as desired. By first estimating the dry weights of the samples and then weighing them periodically during the drying run, the progress of the drying of the load may be kept track of currently.

How many samples to take will require judgment. They must be representative, but the more uniform and regular the drying conditions are in the kiln and the more uniform the material to be dried, the fewer will be required. Ordinarily at least four samples, two placed on the entering air side of the pile and two on the leaving air side, will be required, and frequently double this many.

Dry weight of the sample pieces is readily estimated as follows: Let A_1 and B_1 be the wet weights of the disks, A_0 and B_0 their oven dry weights. Let W_1 be the wet weight of the sample and W_0 its dry weight which is sought.



DISKS CUT FROM CASEHARDENED MAPLE AND OAK BOARDS.

The alternate ones on the left show the condition of the boards when first dried; those on the right show reversal of stresses brought about by steaming the same boards at a slight pressure.

$\frac{(A_1+B_1)-(A_o+B_o)}{(A_o+B_o)}\times 100=P_1$ will be the original moisture per cent of the sample, in terms of oven dry weight. Then its dry weight W_o will be

$$\frac{100\ W_1}{100+P_1}=W_o$$

If W_n be its current weight at any time, its moisture per cent will evidently be

$$\frac{W_n-W_o}{W_o}\times 100=P_n$$

These current values should be plotted on cross-section paper in the form of curves showing the progress of drying; and the temperature, humidities, etc., should be also plotted on the same sheet, as shown in figure 1.

AVERAGE MOISTURE TEST.

The average moisture is determined by cutting a disk clear across the stick, far enough away from the ends to avoid the effect of end drying. One inch is a suitable thickness for this disk, but the exact thickness is immaterial. The disk should be weighed upon a sensitive balance immediately after cutting, before it has had time to lose or absorb any moisture from the air on the freshly cut surfaces. It is then to be dried in an oven, preferably at a temperature between 200° F. and 220° F., never above 230° F. When the disk has ceased to lose weight, which will require from one to two days' time for a wood like oak, it is again weighed. The loss in weight is the moisture content, and this quantity divided by the oven dry weight times 100 gives the "*moisture per cent*" as a standard, as determined by the equation for finding P_n, given above.

MOISTURE DISTRIBUTION TEST.

The moisture distribution disk should be sliced up into an outer layer ¼ inch thick and an inner core ½ inch thick. The outer and inner parts should be weighed separately immediately, and their moisture content determined in the ordinary way, by drying in an oven at a temperature between 200° F. and 220° F., never above 230°.

CASEHARDENING TEST.

Casehardening as well as moisture distribution tests should be made from time to time. Two disks about ¾ inch in thickness should be cut, one of which is to be slotted in the longest direction so as to form two outer prongs, each ⅜ inch thick, and two inner prongs of the same thickness, as shown in Plate IX. The slots should extend to within ⅜ inch of the opposite side.

The indications of casehardening have been fully discussed elsewhere.

DRYING RECORDS.

The drying conditions can be best represented by means of a curve on cross-section paper, like those shown in the specifications in Appendix I. The temperatures and humidities in the curves are those of the air as it enters the pile of lumber; that is, in the flue in water-spray or condenser kilns or in places to be chosen as explained in the discussion of other kilns. The humidity will naturally be higher and the temperature lower where the air is leaving the pile on the sides, or at other portions of the pile. Records should be plotted currently in order to keep track of the progress of the drying operation.

TIME OF DRYING.

The time of drying will vary considerably in different kilns, depending upon the size and form of pile and the circulation. Since the run will be governed by that portion of the pile subjected to the most severe conditions, it necessarily follows that other portions will be relatively slower in drying; and if the air circulation is poor or the pile is very large or close, it may be necessary to continue to hold the final conditions for a considerable time after the material in the hottest portion has reached the proper condition for removal. The poorer the conditions of circulation, the longer will be the time required and the greater will be the discrepancy

in final moisture contents in different portions of the pile. It may even be desirable, in extreme cases of this kind, to raise the final humidity somewhat to prevent part of the stock from becoming too dry while the lagging material is drying down to the required condition. The time element of the drying curve is therefore not included in the specification given in Appendix I. Air-dried or partially dried material requires, of course, proportionally less time to dry. It is well to start with the drying conditions the same as for green material, but in a few days they may be reduced to those given on the curve corresponding to the actual moisture content of the wood.

As air-dried material is very apt to be casehardened it is generally desirable to begin with a preliminary steaming treatment at about 160° for 24 hours in order to remove the surface stress and to remoisten the outer surface. Immediately after the steaming, the temperature and humidity should be reduced to those used at the start—120° and 80 per cent for spruce, for example.

REMOVAL OF CASEHARDENING.

Casehardening, if it develops, may be removed by a steaming treatment at 170° or 180° for ½ to 1½ hours, according to requirements, either during the drying or at the end of the run, a day or so before removal from the kiln. Oak, however, should be steamed at lower temperatures, not over 160°. This may be accomplished by turning boiler pressure steam into perforated steam pipes properly arranged for the purpose. The $\frac{5}{16}$-inch holes should be about 6 inches apart and so placed as to produce a high circulation through the pile of lumber.

Another means of accomplishing this result is to raise the humidity considerably at the end of the run without raising the temperature, thus allowing the outer surface to reabsorb moisture. This relieves the set condition and allows normal shrinkage to be resumed.

Which method is the best to use will have to be determined by the operator to suit the special conditions and species of the material.

MOLD.

Mold is likely to form on some woods, especially green oak and walnut, during the first part of the operation. Aside from retarding the circulation it does not injure the stock, but it must not be allowed to develop. It may be removed by steaming for half an hour or so at 160° F. or over, providing the circulation is sufficient to carry this temperature well through the pile.

APPENDIX I.

DRYING SPECIFICATIONS FOR AIRPLANE STOCK.

At the beginning of the war, the Forest Service was already in possession of knowledge, derived from years of experimental study, to enable it to offer immediately a method by which it was believed that kiln drying could be accomplished without injury to the material. The Forest Service was in a better position than any other organization or individual to recommend suitable methods and apparatus for drying airplane stock. Drying specifications were prepared for the Signal Corps, based on the knowledge and experience then available. They were first drawn on July 2, 1917, and have been employed without significant changes.

The necessity for establishing beyond question the safety of the original drying conditions given in these specifications, however, was apparent, as well as the need to ascertain their application to untried species and to establish limiting conditions as to severity of treatment beyond which it would be unsafe to go. This called for an exhaustive series of strength tests upon material which had been kiln dried under different conditions and a comparison not only with matched green specimens, but likewise with matched specimens which had been set aside and air dried under most favorable conditions. The investigation which was undertaken immediately by the Madison Laboratory of necessity required considerable time before definite conclusions could be drawn, since the matched samples had to become thoroughly air dry. Tests are still in progress, but sufficient results have now been obtained to establish for a certainty the safety of the conditions prescribed in the original specifications prepared in July, 1917. These results are reported in the monograph entitled "The Effect of Drying on the Strength of Airplane Woods."

The following is the specification as finally slightly modified and adopted by the Signal Corps:

[Signal Corps, United States Army.]

SPECIFICATION FOR GENERAL KILN-DRYING PROCESS FOR AIRPLANE STOCK.

[Nos. 20500 and 20500-A.]

GENERAL.

1. This specification covers the general requirements of the Signal Corps for kiln-drying of wood for airplane stock.

2. The kiln-drying operations shall be so conducted that the wood will not lose any strength, toughness, or other physical property.

MATERIAL.

3. Only one species and approximately one thickness shall constitute a kiln charge. A difference of not to exceed ½ inch in thickness of single pieces will be allowed.

PILING.

4. The boards shall be piled so that the horizontal width of the spaces between them will be at least 1 inch for each inch of board thickness, but in no case shall the horizontal width of such spaces exceed 3 inches. The boards must be held flat and straight while drying.

5. For stock up to 4 quarters (1 inch) in thickness, the crossers shall be at least 1 inch thick and not over 1½ inches wide.

6. For stock from 4 to 12 quarters (1 to 3 inches) in thickness, the crossers shall be at least 1½ inches thick and not over 1½ inches wide.

7. For stock over 12 quarters (3 inches) in thickness the thickness of the crossers shall be increased in the above proportion but must not exceed 2 inches in any case.

8. The crossers shall be placed directly over one another and not over 3 feet apart in the courses.

9. The lumber must be so disposed in the kiln as to permit of easy access on both sides of the pile and the taking of temperature and humidity readings whenever required by the inspector.

INSTRUMENTS.

10. At least one recording thermometer or recording hygrometer of approved make shall be used in each dry kiln compartment.

11. Recording thermometers or hygrometers shall be checked at least once every kiln charge, with a standard thermometer or a glass thermometer calibrated to an accuracy of 1° F. This comparison shall be made with the thermometers placed so as to record the maximum temperature of any portion of the pile.

12. *Thermometers.*—Thermometer bulbs must be shielded from direct radiation of steam pipes, wet lumber, cold walls or surfaces, and must receive a free circulation of air.

13. The inspector may, at his discretion, place other thermometers at any point in the pile.

14. *Hygrometer.*—Humidity readings shall be made at least three times daily or more often as the inspector may desire, according to standard methods approved by the inspector, at the same points where the recording thermometers or hygrometer bulbs are placed.

APPENDIX I.

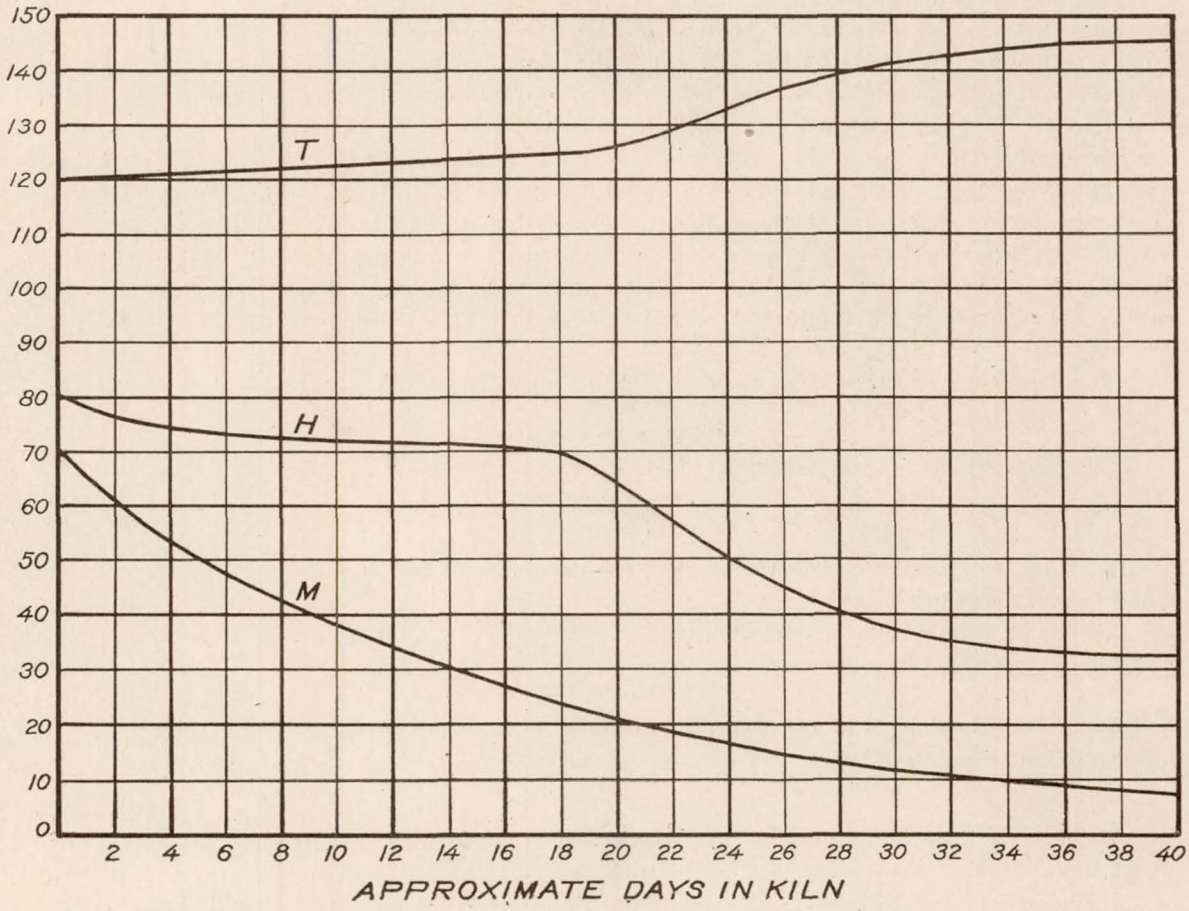


FIG. 2.—SPECIFICATION SCHEDULE, TABLE 1, FOR AIRPLANE WING-BEAM STOCK. T, TEMPERATURE ° F.; H, RELATIVE HUMIDITY, PER CENT; M, NORMAL DRYING CURVE, PER CENT OF MOISTURE; ALL ON ENTERING AIR SIDE OF PILE OF LUMBER.

15. The following shall constitute a standard method: Use a glass or recording wet and dry bulb hygrometer with distilled water and with the wick changed at least once a week; produce a circulation of air past the wet bulb of at least 5 feet per second before reading.

16. Hygrometer bulbs must be shielded from direct radiation of steam pipes, wet lumber, cold walls or surfaces, and must receive a free circulation of air.

STEAMING.

17. *At the beginning of the drying operations.*—Green wood is to be steamed at a temperature not to exceed 15° F. higher than the initial drying temperature specified in Tables 1 and 2, for 6 hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent, in every portion of the pile.

18. Previously air-dried wood is to be steamed at a temperature not to exceed 30° F. higher than the initial drying temperature specified in Tables 1 and 2, for 8 hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent in every portion of the pile.

19. *Near the end of the drying.*—If on official test the stock shows serious casehardening it shall be steamed at a temperature not to exceed 20° F. higher than the final drying temperature specified in Tables 1 and 2, for not more than 3 hours. After steaming it shall be redried.

TEMPERATURE AND HUMIDITY.

20. Operating conditions are specified in Tables 1 and 2, but lower temperatures and higher humidity conditions are permissible.

21. The progression from one specified stage to the next must proceed without abrupt changes.

22. *Green wood (above 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in Tables 1 and 2 by 5° F. for each inch increase in thickness.

23. *Air-seasoned wood (below 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in Tables 1 and 2 by 5° F. for each inch increase in thickness.

TABLE 1.

Stage of drying.	Drying conditions.	
	Maximum temperature, Fahrenheit.	Minimum relative humidity, per cent.
At the beginning	120	80
After fiber saturation is passed (25 per cent)	125	70
At 20 per cent moisture	128	60
At 15 per cent moisture	138	44
At 12 per cent moisture	142	38
At 8 per cent moisture	145	33
Final	145	33

24. Table 1 applies to the following woods:

Ash, white, blue, and Biltmore.
Birch, yellow.
Cedar, incense.
Cedar, northern white.
Cedar, western red.
Cedar, Port Orford.
Spruce, Sitka.
Cypress.
Pine, sugar.
Pine, white (Idaho or eastern).
Spruce, eastern (red or white).
Douglas fir.

TABLE 2.

Stage of drying.	Drying conditions.	
	Maximum temperature, Fahrenheit.	Minimum relative humidity, per cent.
At the beginning	105	85
After fiber saturation is passed (25 per cent)	110	73
At 20 per cent moisture	117	62
At 15 per cent moisture	129	46
At 12 per cent moisture	135	42
At 8 per cent moisture	135	40
Final	135	40

25. Table 2 applies to the following woods:

Cherry.
Mahogany.
Oak, white and red.
Walnut, black.
Maple.

TESTS DURING DRYING.

26. Samples shall be inserted in the pile in such manner that they will be subjected to the same drying conditions as that portion of the pile where inserted. They shall be so placed

that they can be removed for periodical weighing in order to ascertain the average moisture content of the pile at any time.

27. Three samples shall be used for each 10,000 board feet or less of material in the pile. Each sample is to be 2 feet long and shall not be cut nearer than 2 feet to the end of one of the pieces to be dried.

28. The original moisture content of the samples shall be determined from sections 1 inch

APPENDIX I.

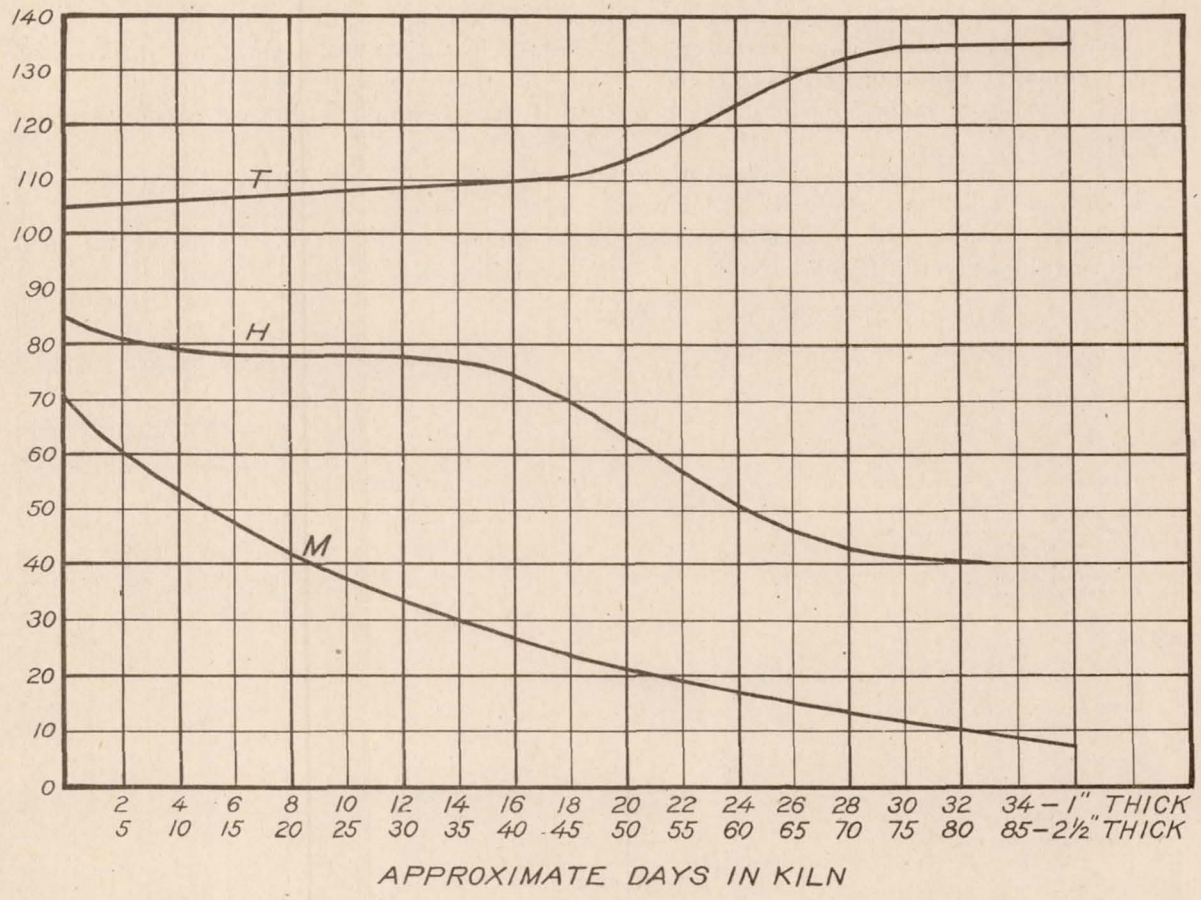


FIG. 3.—SPECIFICATION SCHEDULE, TABLE 2, FOR PROPELLER STOCK AND HARDWOODS.

Nomenclature as in figure 2.

thick cut from both ends of the sample at the time it is sawed from the stick. This determination shall be made as provided in specification No. 20504–A.

29. Before placing them in the pile, the ends of the samples must be given a thorough coating of asphaltum varnish to prevent end drying.

30. The samples shall be weighed to an accuracy of one-tenth of 1 per cent immediately after cutting the moisture sections and before placing in the kiln. They shall be weighed at least daily when the time of drying is 10 days or less, and at least every other day when the time of drying is more than 10 days.

31. The samples shall be placed in the pile and distributed so that they will be exposed to the average, most rapid, and slowest drying, except that they shall not be placed on the top or bottom layers. The samples placed in the portion of the pile where drying is most rapid shall control the regulation of the temperature and humidity.

32. After obtaining the dry weight of the samples, the average moisture condition of the pile during the drying shall be determined after each weighing.

33. The following example will illustrate the method employed:

Original weight of sample = 7.35 pounds.
Original moisture per cent (average of the two 1-inch sections) = 47.
Calculated dry weight of sample = 7.35 divided by 1.47 = 5.00 pounds.
Current weight = 6.23 pounds.
Moisture in samples = 6.23 − 5.00 = 1.23 pounds.
Current moisture per cent = (1.23 divided by 5.00) × 100 = 24.6.

34. Continuous and permanent records must be kept of the temperature and humidity observations and the percentage of moisture in the lumber in the kiln.

TESTS AFTER DRYING.

35. Standard moisture content and casehardening tests shall be made before the lumber is removed from the kiln. Material for these tests shall be taken from four boards for each 5,000 board feet or less of material in the pile. Pieces selected must fairly represent the dried stock and shall be taken from different parts of the pile. At his discretion the inspector may select other pieces for tests. Sections for these tests shall not be cut nearer than 2 feet to the ends of the pieces.

36. Three adjacent sections, 1 inch thick, shall be cut from the centers of each test piece of stock. *Each section must be weighed within five minutes to prevent moisture evaporation.*

37. *The first section.*—(A, fig. 4) shall be dried whole and the average moisture content obtained as provided in specification No. 20504–A.

38. *The second section.*—(B, fig. 4) moisture distribution section shall be cut into an outer shell ¼ inch wide and an inner core ½ inch wide. The moisture content of the outer shell and inner core shall be determined.

39. *The third section.*—(C, fig. 4) shall be sawed parallel to the wide faces of the original board into tongues or prongs, leaving about ½ inch of solid wood at one end of the section. For material less than 2 inches thick two saw cuts shall be made and for material more than 2 inches thick five saw cuts shall be made. In sections having six prongs the second prong from each side shall be broken out, leaving two outer and two central prongs. The center prong shall be removed from sections having only three prongs.

40. The third section shall then be allowed to dry for 24 hours in the drying room and any curving of the prongs noted.

41. If the prongs remain straight, perfect conditions of stress and moisture content are indicated.

42. If the outer prongs bend in, conditions of casehardening are indicated.

43. Only very slight casehardening is permissible.

FINAL MOISTURE CONDITIONS.

44. An average dryness of approximately 8 per cent, unless otherwise specified, shall be required. A moisture content of from 5 to 11 per cent is permissible in individual sticks.

45. The variation in moisture content between the interior and exterior portions of the wood, as shown by the "moisture distribution section" provided for in paragraph 38, must not exceed 4 per cent.

SEASONING.

46. Before manufacture the wood shall be allowed to remain in a room, with all parts under uniform shop conditions, at least two weeks for 3-inch material, and other sizes in proportion.

STEAMING AND BENDING OF ASH FOR LONGERON CONSTRUCTION.

47. The ash shall be cut in the form of rough squares sufficiently large to allow for shrinkage and finish.

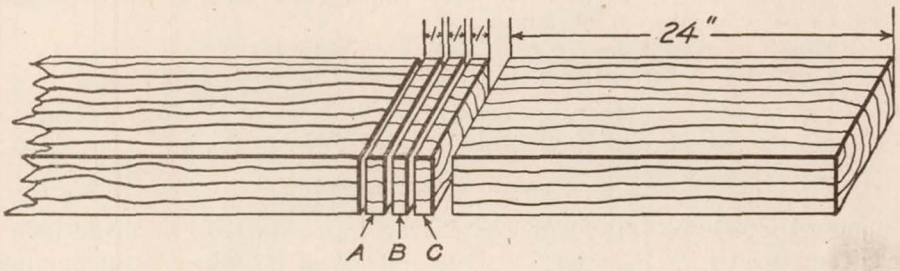
48. Where it is necessary to bend this material, it shall be steamed in the green condition (more than 18 per cent moisture), bent on forms, and then kiln dried as provided in paragraph 23.

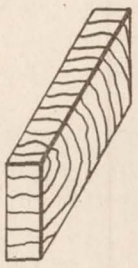
49. Steaming shall be conducted at a temperature not to exceed 212° F. for a period not longer than six hours, and the bending shall be accomplished while the material is hot.

INSPECTION.

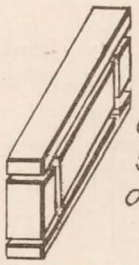
50. At all stages of the process the lumber shall be subject to inspection by the Inspection Department of the Signal Corps under its Manual of Inspection.

APPENDIX I.

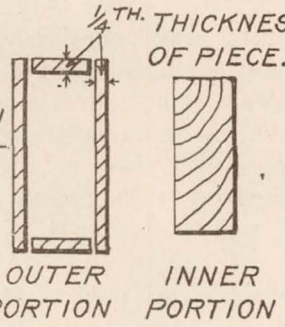




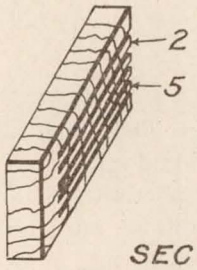
SECTION A
TO BE WEIGHED, THEN OVEN-DRIED, THEN REWEIGHED TO DETERMINE AVERAGE MOISTURE CONTENT OF PIECE.



SECTION B
OUTER MARGIN SAWED OR SPLIT OFF AS SHOWN.

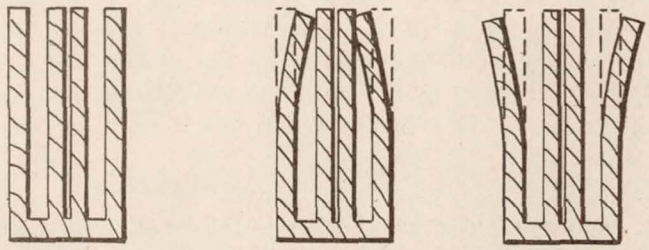


OUTER AND INNER PORTION WEIGHED, DRIED AND REWEIGHED SEPARATELY TO DETERMINE DIFFERENCE IN MOISTURE CONTENT.



SECTION C
THICK STOCK SAWED AS SHOWN FOR CASEHARDENING TEST, PRONGS 2 AND 5 TO BE BROKEN OUT.

SECTION TO BE DRIED BEFORE CONCLUSION AS TO CASE HARDENING IS MADE.



NOT CASE HARDENED

CASE HARDENED NOT PERMISSIBLE IN AIRPLANE STOCK

SHOWING EFFECT OF OVERSTEAMING

FIG. 4.—SPECIFICATION NO. 20500-A, MOISTURE AND CASEHARDENING TEST SPECIMENS.

51. The inspector shall mark all lumber with the official acceptance or rejection symbol of the Signal Corps.

52. The inspector shall have free access to every part of the kiln at all times and shall be afforded every reasonable opportunity to satisfy himself that this specification is being complied with.

APPENDIX II.

CONSTANT DEW-POINT SCHEDULE FOR DRYING DOUGLAS FIR, SPRUCE, AND SIMILAR WOODS.

An improvement over the schedule in the original specifications for drying species listed under Table I of Signal Corps, United States Army, specification 20500–A, was worked out, by the use of a constant dew point of 115°, and is shown in Plate III. This somewhat simplifies the control of the operation, especially in the water-spray kilns, where the dew point is used as the controlling element of the humidity. The schedule here given is equally good with the former, and has already been put into use.

If marked casehardening becomes apparent it should be removed by steaming for two or three hours at 160° once or twice near the end of the run, as indicated by "S" in the plate of curves. If no very severe casehardening develops, a high humidity for one day just before the close of the run, without raising the temperature, may suffice. Steaming at a temperature of 160° for not over one hour should always be resorted to if severe casehardening develops at any stage of the run, but is not ordinarily necessary if the given schedule be adhered to.

In figure 5, T is the temperature of the air entering the pile of lumber, in degrees Fahrenheit, D is the dew point, H is the relative humidity per cent, and M is the normal drying curve of the lumber on the entering air side of the pile, in percentage of the dry weight.

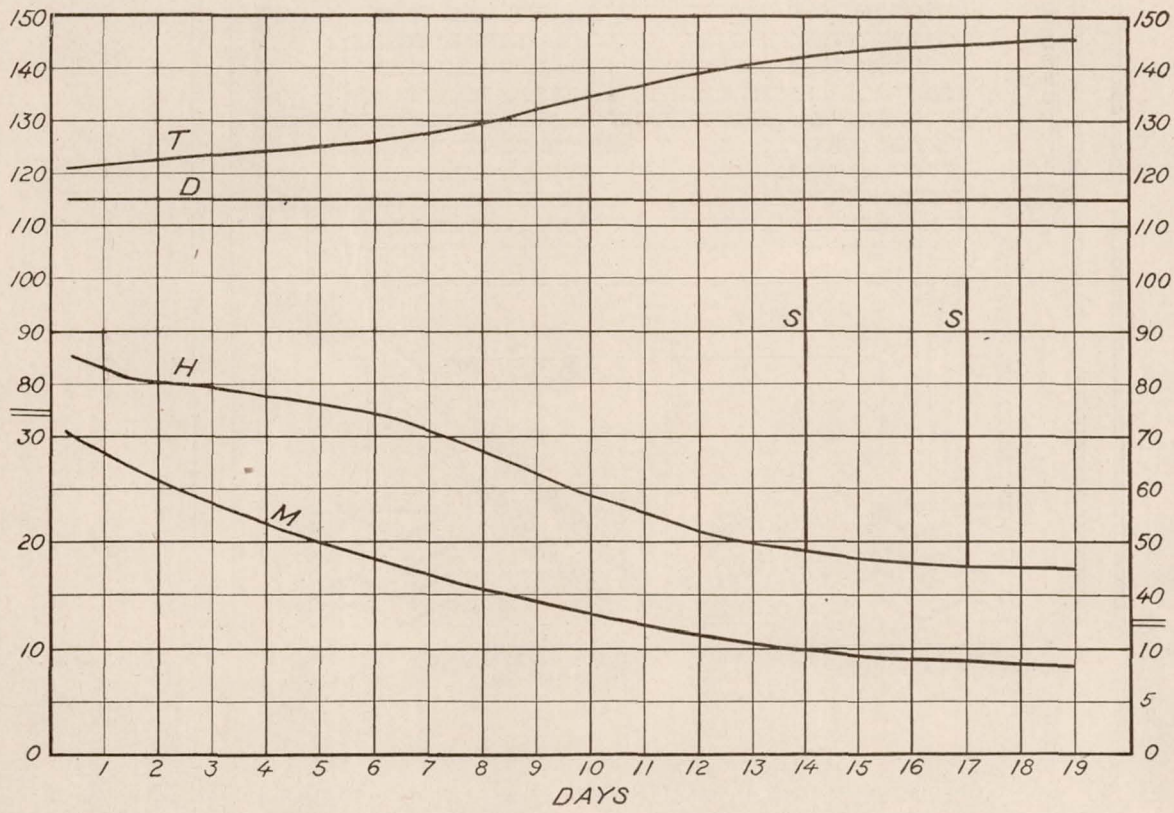


FIG. 5.—CONSTANT DEW-POINT SCHEDULE FOR AIRPLANE WING-BEAM STOCK MAY BE USED IN PLACE °F TABLE 1 SCHEDULE, WITH EQUALLY GOOD RESULTS.

APPENDIX III.

THE FOREST SERVICE WATER-SPRAY KILN.

In figure 6 is shown the cross section of a Forest Service water-spray kiln which has proved successful in drying airplane stock.[1] While airplane woods can be satisfactorily dried in

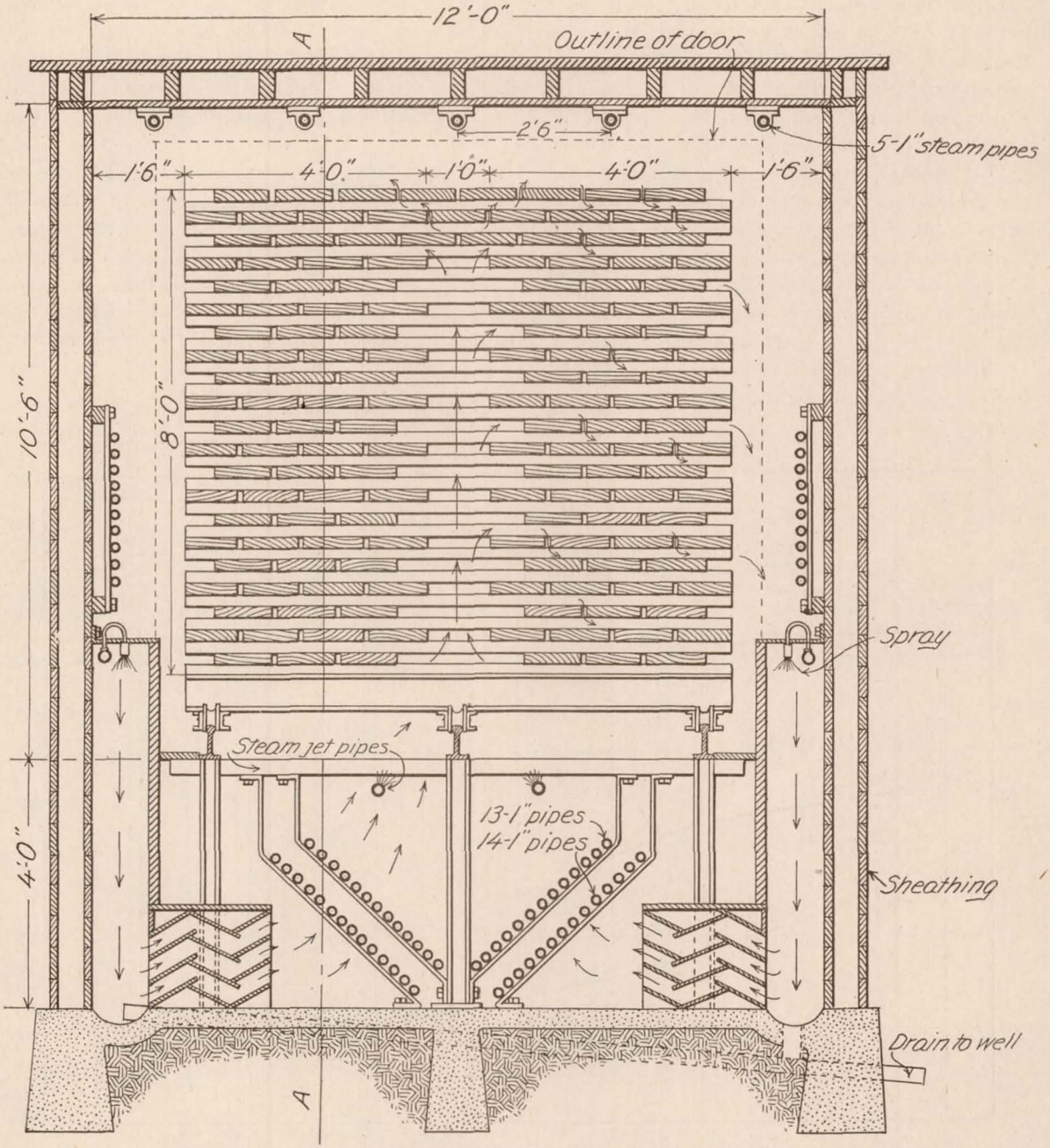


FIG. 6.—DIAGRAMMATIC CROSS-SECTIONAL VIEW OF THE WATER SPRAY DRY KILN.

various forms of kilns, the water spray is recommended for the purpose on the basis of considerable experience. Since many of these are already in use for this purpose only a brief description will be given.

The essential feature of this kiln is control of the humidity and the production of air circulation by means of a series of water sprays, spaced short distances apart and running the entire length of the kiln and operating in narrow flues about 12 to 16 inches in width and about 6 feet deep.

One flue is placed on either side of the kiln, as shown in figure 6; or a single flue may be placed in the center. The spray of water is directed downward with considerable force, and produces a large movement of air, which, after leaving the baffle plates at the bottom of the spray chambers, rises through the heating coils and upward through the central flue between the piles of lumber; thence it passes downward and outward to the spray flues again.

The humidity is regulated by the temperature of the spray water, the air being brought to a condition of complete saturation in its passage through the sprays of water. Cold water reduces humidity and hot water raises it, since the temperature of the air as it leaves the bottom of the spray chambers is the dew point of the air after it is heated in passing through the heating pipes. Thus, the humidity of the air delivered to the lumber is controlled by controlling the dew-point temperature.

Zigzag baffle plates are arranged at the bottom of the spray chambers to remove all free particles of water and leave the air in a clear saturated condition as it enters the steam pipes Condensers are also placed above the spray chambers, to be used near the end of the run when a low humidity but not much air circulation is required, and a high-pressure steam spray pipe is placed in the spray chambers for use in relieving casehardening. There are no ventilators, and the kiln is tightly closed, the same air being recirculated over and over.

Only these essential parts need be mentioned here, since in this brief discussion a complete design of the kiln is not intended and the planning of new kilns or the modification of old ones would need to be taken up in detail according to requirements.

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[1] This kiln has been patented by the author and dedicated to the public, No. 1019743, Mar. 5, 1912; No. 1019999, Mar. 12, 1912; and No. 1228989 June 5, 1917.

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REPORT No. 66

GLUES USED IN AIRPLANE PARTS

COMPILED BY

S. W. ALLEN, Industrial Examiner in Forest Products
and T. R. TRUAX, Wood Technologist

FOREST PRODUCTS LABORATORY
FOREST SERVICE

UNITED STATES DEPARTMENT OF AGRICULTURE
(In Cooperation with the University of Wisconsin)

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REPORT No. 66.

GLUES USED IN AIRPLANE PARTS.

By S. W. Allen and T. R. Truax.

This report was prepared for the National Advisory Committee for Aeronautics and presents the results of investigations conducted by the Forest Products Laboratory of the United States Forest Service, at the request of and with funds provided by the Bureau of Construction and Repair and the Bureau of Steam Engineering of the Navy Department, and the Bureau of Aircraft Production of the War Department. Some of the general statements are taken from the literature on glues existing previous to the time that the laboratory undertook this line of investigation.

GENERAL STATEMENT ON KINDS AND SOURCES OF GLUE.

There are many kinds of glue, some of which have been known for a long time. The kind to be used in any particular case depends upon the character of the material to be held together and upon the use to which the finished article is to be put. Strength, for instance, is usually the important requirement for glue to be used for joint work; cheapness may be more important than strength in the manufacture of low-grade plywood and other inexpensive articles; and water-resistance is demanded of the glues to be used in airplanes, certain kinds of sporting goods, and other glued work which is to be exposed to the weather or to high humidity.

For the purpose of this discussion, glues will be divided into five types, which will be designated as follows:

1. Animal glues, which are made from the hides, hoofs, horns, bones, and fleshings of animals, principally cattle. These glues must be mixed with water and melted.

2. Liquid glues, which are commonly made from the heads, skins, bones, and swimming bladders of fish. Some liquid glues, however, are made from animal glue and from other materials. They come in prepared form ready for immediate use.

3. Vegetable glues, which are made from starch, usually cassava starch, and sold in powdered form. Ordinarily they require heating with water and alkali for preparation.

4. Casein glues, which are made from casein, lime, and certain other chemical ingredients. They are commonly sold in powdered form, requiring only the addition of water.

5. Blood albumin glues, which are made from black soluble blood albumin, a product recovered from the blood of animals. These glues must be mixed just before use, since they deteriorate rapidly in standing.

ANIMAL GLUES—THEIR MANUFACTURE, PREPARATION, AND APPLICATION.

MANUFACTURE OF ANIMAL GLUE.

The process of making animal glue is briefly as follows: The stock is washed and treated to remove dirt and grease, and then boiled to convert the glue-forming substances into a glue solution. This solution is concentrated by evaporation until it will form a jelly on cooling. The jelly is then cut into various forms and dried.

There are many details and variations which depend upon the kind of stock used and the plant in which the glue is made, and which affect more or less the character of the resultant glue. Bones are sometimes boiled without first removing either dirt or grease. This practice

naturally fails to produce a high-quality glue. Bones may or may not be treated with acid to remove the calcium salts before cooking; and this also influences the glue quality. In cooking, the temperature and time must be carefully watched, as over-cooking may materially reduce the strength of the glue. The stock is usually boiled with fresh water several times. The first boiling or first run gives the best glue, and each later a weaker.

As the solution of glue from the boiling kettles is too weak to form a jelly which can be handled, it must be concentrated. This is done by boiling off the water in vacuum dryers until the percentage of glue in the solution is high enough to make a firm jelly on cooling. If the temperature rises too high during the concentrating process the quality of the glue may be lowered.

When sufficiently concentrated the glue solution is cooled by refrigeration, either after being run into pans or as it runs upon a traveling belt. As it cools it forms a jelly firm enough to handle. The jelly in the pans is removed, sliced with wires or a knife, and placed upon screens to dry. If a belt is used the jelly is formed in a continuous sheet, which is cut into sections and placed on screens as it travels along. The screens are then placed in a drying chamber and left until the glue is dry. Glue may be easily injured during the drying process if the temperature conditions are not properly controlled.

The form of the glue when dry depends upon the shape in which it was placed upon the screens. If carefully sliced to the proper thickness regularly shaped cakes will be formed. The sheet glue from the belt breaks into thin irregularly shaped pieces as it comes from the drying nets. This is commonly run through a machine to break it into smaller pieces, in which shape it is shipped as flake glue. Other forms of glue are also made, and any of the forms may be subsequently ground and sold as ground glue.

Sometimes mineral matter such as barium sulphate, white lead, chalk, zinc oxide or whiting is added to the glue after it has been concentrated, but before it is cooled. This gives it a light color and makes it opaque, which is a feature desired by some consumers.

Nominal grades can not be relied upon when purchasing animal glue for high-class work. It is necessary for the purchaser who buys on bids to specify his requirements and then provide means to insure that the glue furnished by the manufacturer is up to these requirements. The variety in character, color, form, strength, and other characteristics of animal glues is almost without limit. A system of classification, based chiefly on the jelly strength, was devised a long time ago by Peter Cooper. By means of this system it is possible to group the great variety of glues into a relatively small number of classes or grades. The grades established by Cooper were designated, beginning with the strongest, A extra, 1 extra, 1, 1X, 1¼, 1⅜, 1½, 1⅝, 1¾, 1⅞, 2. There are now on the market glues stronger than A extra, and glues weaker than 2, for which there is no standard Peter Cooper grade. This system of grading, however, appears to be but little used to-day by manufacturers, except occasionally for comparative purposes. Each manufacturer has his own system of grading, which he keeps more or less secret, and to the general buying public the grades mean little or nothing. It is sometimes claimed, also, that the Peter Cooper grades of to-day are not the same as those originally established.

MIXING AND APPLICATION OF ANIMAL GLUE.

In using animal glue various precautions must be observed if satisfactory results are to be obtained. By improper use a very high-grade glue may be made to give poor joints. It is important, first, to find out the right proportion of glue and water to use in order to get the best results with the wood that is being employed and the conditions under which the work is being done. This is largely a matter of experience, but it can also be determined by strength tests. When the right proportions have been decided upon, they should be strictly adhered to thereafter, and the glue and water should be weighed out when making up a new batch of glue rather than measured or guessed at. Clean, cold water should be used, and the mixture thoroughly stirred to prevent lumps. It should then stand in a cool place until the glue is

thoroughly water-soaked and softened. This may take only an hour or two, or it may take all night, depending upon the size of the glue particles. It should then be melted over a water bath. The temperature should not be allowed to go higher than about 150° F.; high temperatures and long-continued heating reduce the strength of the glue. The glue pot should be kept covered as much as possible in order to prevent the formation of a skin or scum over the surface of the glue.

The room in which the glue is used should be as warm as possible without causing too much discomfort to the workman, and it should be free from drafts. In a cold drafty room the glue cools too quickly and may set before the joint has been put into the clamps. The result is a weak joint. It is also considered good practice to warm the wood before applying the glue, but it should not be heated long enough to cause an appreciable moisture change. Wood should never be glued when it is colder than room temperature, and, of course, only thoroughly seasoned wood should be used. Since high-strength animal glues set so quickly on cooling, they should be applied and the joints clamped as quickly as is consistent with good workmanship.

In clamping, the pressure should be evenly distributed over the joint so that the faces will be in contact at all points. The amount of pressure to give the best results is a question which has never been definitely settled. Apparently no tests have yet been made to show the best pressure to use on edge or flat grain joints. In gluing veneers it is necessary to use high pressures in order to flatten out the irregularities of the laminations. Pressures as high as 150 pounds per square inch are sometimes used, but it is not established that such high pressures are necessary or desirable. Too much pressure must not be used in gluing surfaced wood, as the glue may be pressed out too completely from the joint, producing a so-called starved joint.

Strict cleanliness of glue pots and apparatus and of the floors and tables of the glue room should be observed. Old glue soon becomes foul and affords a breeding place for the bacteria which cause decomposition. The fresh glue is, therefore, in constant danger of becoming contaminated. Glue pots and brushes should be washed after every day's work. The brushes will remain sweet if kept when not in use in a weak solution of carbolic acid. Glue enough for a day's run only should be mixed at one time, so that mixed glue will not have to be held over from one day to another. If these sanitary precautions are not observed, poor joints may result.

STRENGTH OF ANIMAL GLUE.

The highest grades of animal glue are the strongest glues used in woodworking. Their strength is greater than that of the woods they are used upon, and when they are properly applied they are exceedingly reliable, so long as they are not exposed to moisture. The certified glue used in propeller manufacture was sufficiently strong for the highest type of woodworking, but still higher grades of glue are obtainable. The certified glues were required to have an average shearing strength[1] of 2,400 pounds per square inch, with a minimum of not less than 2,200 pounds per square inch. Most of them, however, actually showed an average shearing strength of between 2,500 and 3,000 pounds per square inch.

The shearing strength of the lower grades of animal glue, such as 1¼ and less, is somewhat lower, but by careful application fairly high values can be obtained from them.

The water-resistance of animal glue is low; but the high grades, which have high jelly strength will stand dampness for longer periods than the low grades, which have low jelly strength.

LIST OF REFERENCES.

In a brief discussion of this nature it is not possible to cover thoroughly all the points touched upon, or even to mention many things which the glue user or inspector should know. Those who wish a fuller knowledge of the subject are referred to the following publications:

[1] See "Testing of Glues," p. 21.

BOOKS.

Agglutinants of all kinds and for all purposes. By H. C. Standage. Pp. 267. D. Van Nostrand Co., New York, 1907. $3.50.

Glue, gelatine, etc. By F. Dawidowsky. Pp. 282, illus. H. C. Baird Co., Philadelphia, Pa., 1905. $3.

Glues and gelatines. By R. L. Fernbach. Pp. 200, illus. D. Van Nostrand Co., New York, 1907. Discusses the manufacture, classification, testing, and analyses of glues and gelatines, and gives information on substitutes. $3.

Glue and glue testing. By Samuel Rideal. Pp. 144, illus. Scott, Greenwood & Son, London, 1901. Discusses the manufacture, testing, and use of glues, especially the chemical side. $4.

The glue book. By J. A. Taggart. Pp. 85, illus. The Republican Publishing Co., Hamilton, Ohio, 1913. Discusses "how to select, prepare, and use glue." $1.

Glue handling. By Friman Kahrs. Pp. 128, illus. Alliance Printing Co., New York, 1906. $1.

JOURNAL ARTICLES.

Specifications and tests of glue. By O. Linder and E. C. Frost. In the proceedings of the American Society for Testing Materials, 1914, Part 2, pp. 509 to 519. Gives the results of tests of cabinet glue.

A study of various tests upon glue. By A. H. Gill. In the Journal of Industrial and Engineering Chemistry, 1915, vol. 7, pp. 102 to 106. Gives the results of tests made at the Massachusetts Institute of Technology.

Glue for use on airplanes. By P. A. Houseman. In the Journal of Industrial and Engineering Chemistry, 1917, vol. 9, pp. 359 to 360. Republished in Aviation, July 1, 1917, p. 462.

The grading and use of glues and gelatine. By Jerome Alexander. In the Journal of the Society of Chemical Industry, 1906, vol. 25, pp. 158 to 161.

LIQUID GLUES—THEIR MANUFACTURE, PROPERTIES, AND USES.

Liquid glues vary over an exceedingly wide range, not only in their appearance and properties but also in their chemical constituency. Most of them are manufactured from the heads, bones, swimming bladders, and other offal from fish.

The process is somewhat similar to that used in the manufacture of animal glues. The offal is thoroughly washed with water and then discharged into extractors and digested with live steam. After digestion the liquid is drawn off and allowed to stand, following which the upper oily layer is removed. The lower gluey solution is then clarified with alum, filtered, concentrated in open vats, and bleached with sulphur dioxide. The resulting glue is a light-brown viscous liquid of extremely disagreeable odor. It is sometimes treated with sodium phosphate or perfumed in order to make the odor less offensive. Dextrine, certain gums and resins, starch, casein, rubber, and bitumen also find occasional use in the manufacture of liquid glues.

A few liquid glues are made with animal glue as a base by treating the latter with a chemical agent that destroys the power of the glue to form a jelly, and by mixing it with a thinner which evaporates when the glue is used and permits it to set.

A good liquid glue has certain advantages. It can be used cold and spread without any preparation whatever. On the other hand, it is not generally so strong as high-grade animal or casein glues, is more expensive, and not so widely marketed. Its use in airplanes is confined to repair work and well-protected parts. The majority of purchasers have no way of knowing in advance how satisfactory a liquid glue will prove to be. Some preliminary studies made at the Forest Products Laboratory indicated that the strength of liquid glue varies with its "body" or viscosity. As a rule, a thick viscous glue will give high strength and vice versa. The body or viscosity is also important because it influences the amount of glue which may be maintained in a joint when pressing. A thin glue will spread a larger area, but the layer on the wood will be so thin that there is danger of squeezing it out under pressure and producing a weak, or "starved," joint. Other qualities desirable in liquid glues are ability to dry and set rapidly when spread on wood surfaces, and to remain liquid while in the container and over ordinary ranges of temperature.

CASEIN GLUES—THEIR MANUFACTURE, PREPARATION, AND APPLICATION.

One of the many direct results of the war has been the introduction of casein glues into the woodworking industries of this country. Previously these glues had been used in Europe to a limited extent in bookbinding and cabinet work, but their production on a large scale was unknown. In the United States the use of casein glues is more recent and their development has been more rapid than in Europe. At the beginning of 1918 only one plant in this country was manufacturing a water-resistant casein glue. With our entrance into the war the demand of the Army and Navy for waterproof ply-wood enormously increased the production, so that by the latter part of 1918 four different companies were manufacturing casein water-resistant glues and the Forest Products Laboratory had developed several formulas for making them.

TYPES OF CASEIN GLUES.

There are, in general, two types of casein glues which for convenience may be designated as prepared glues and wet-mix glues. In the former, the glue components are mixed dry; while in the latter, the ingredients are added separately and at different times during the mixing process. Casein glues on the market are of the dry-mix type; that is, they are prepared and shipped ready to add to water. The Forest Products Laboratory has done a large amount of work in developing casein glues, and some of the best formulas are of the wet-mix type.

MANUFACTURE OF CASEIN.

The principal constituent of all casein glues is casein, a product obtained from milk. When milk sours naturally, casein is precipitated and appears as "curd." When produced in this way it is known as self-soured or naturally soured casein. Various acids may be added to the milk to precipitate the casein, the principal ones used being hydrochloric (muriatic) and sulphuric. Rennet is also used to some extent as a precipitating agent.

The usual steps in the production of casein are: (1) Removal of fat in the form of cream from the milk, which is usually accomplished by means of a separator; (2) precipitation of the casein; (3) washing to remove the acid and other impurities; (4) drying; and (5) grinding to a powder. The care used in these various steps of manufacture has a large effect upon the glue-making properties of the casein.

The principal requirements of casein to make it desirable for glue making are: (1) A low percentage of impurities such as acid, moisture, and fat; (2) freedom from sour odors; (3) clearness and uniformity of color; and (4) fineness of particles. By grinding a casein to fine particles a minimum of time is required in the mixing and a more uniform glue is obtained. A casein ground to pass through a screen of from 50 to 60 meshes to the inch will give good results.

MANUFACTURE OF GLUE.

To produce glue, casein is mixed with other ingredients, the chief of which are lime and water. These three constituents alone will give a glue of good water-resistant properties, but of short life. Other ingredients are, therefore, added to increase the working life and the water resistance and to improve the other qualities of the glue. Caustic soda, sodium fluoride, and sodium silicate are used in some patented formulas. They all lengthen the life of the glue, and sodium fluoride probably gives the glue antiseptic properties. Still other ingredients are added to give the glue some particularly desired property. Oils are usually added to the dry-mix glue to prevent dusting in handling the glue. Formulas vary, therefore, not only in materials used but also in the proportions of different ingredients.

Several formulas for mixing casein glues have been developed at the Forest Products Laboratory. One of the best of these, with a discussion of the method of mixing and a description of materials required, follows.

FORMULA—GLUE NO. 4-A.[1]

100 parts casein, 130 to 280 parts water } soak 15 minutes
15 to 22 parts hydrated powdered lime, 90 parts water } mix
} mix
70 parts silicate of soda
} mix

METHOD OF MIXING.

The proper quantity of water is introduced into the glue pot, and the mixing blade is brought into action at a speed corresponding to about 50 or 60 revolutions per minute. The stirring is allowed to continue during the addition of the casein to the water and for a few minutes thereafter until the mixture becomes mush-like in consistency through the absorption of the free water by the casein. The blade is then stopped and the mixture allowed to soak.

After a period of 15 minutes the soaking is considered complete and the mixing blade is again brought into action. The lime-water mixture is now added and two or three minutes later the liquid silicate of soda is introduced.

The mixing is allowed to continue for from 20 minutes to one-half hour after the addition of the silicate of soda, whereupon a smooth, freely flowing mixture, of uniform texture and free from lumps, should be produced.

Usually some experience in the mixing of this glue is necessary before satisfactory results can be expected, and it is advisable to have a new operator witness an actual demonstration. This is due to the fact that no precise quantity of water can be prescribed because of the variation in the water-absorbing qualities of different caseins. The criterion of whether or not the proper quantity of soaking water has been added is the viscosity of the finished (mixed) glue. If its consistency is too thin, an excess of water beyond that required has been used, and it is best to reject the batch and try again. Similarly, if the consistency is too thick and heavy, an insufficient quantity of water has been used. The water required for various types of casein lies in the following ranges:

Lactic-acid casein	130 to 170 parts water
Sulphuric-acid casein	170 to 220 parts water
Hydrochloric-acid casein	
Rennet casein	280 parts water

DESCRIPTION OF MATERIALS.

Casein.—It is essential that the casein be of a reasonably pure grade, carefully manufactured, free from offensive odors, not of a dark yellow, dirty, or other objectionable color, and low in fat, as well as in free acid. It should be fine enough to pass through a 60-mesh sieve.

Lime.—A high calcium lime gives satisfactory results, but limes containing a relatively large amount of magnesia can be employed if a quantity sufficient to give the required calcium hydroxide content be used. It can be prepared for use by adding just enough water to fresh quicklime to cause it to slack to a powder. It should then be made fine enough to pass entirely through a 60-mesh sieve. Commercial powdered hydrated limes are also suitable.

Silicate of soda.—The silicate of soda is in liquid form and corresponds to the grade which appears on the market for preserving eggs or for adhesive purposes. The various samples which have given satisfactory results at this laboratory have had analyses included within the following ranges:

[1] U. S. patent No. 1291396 on this process has been granted to Samuel Butterman, of the Forest Products Laboratory, and assigned to the United States Government.

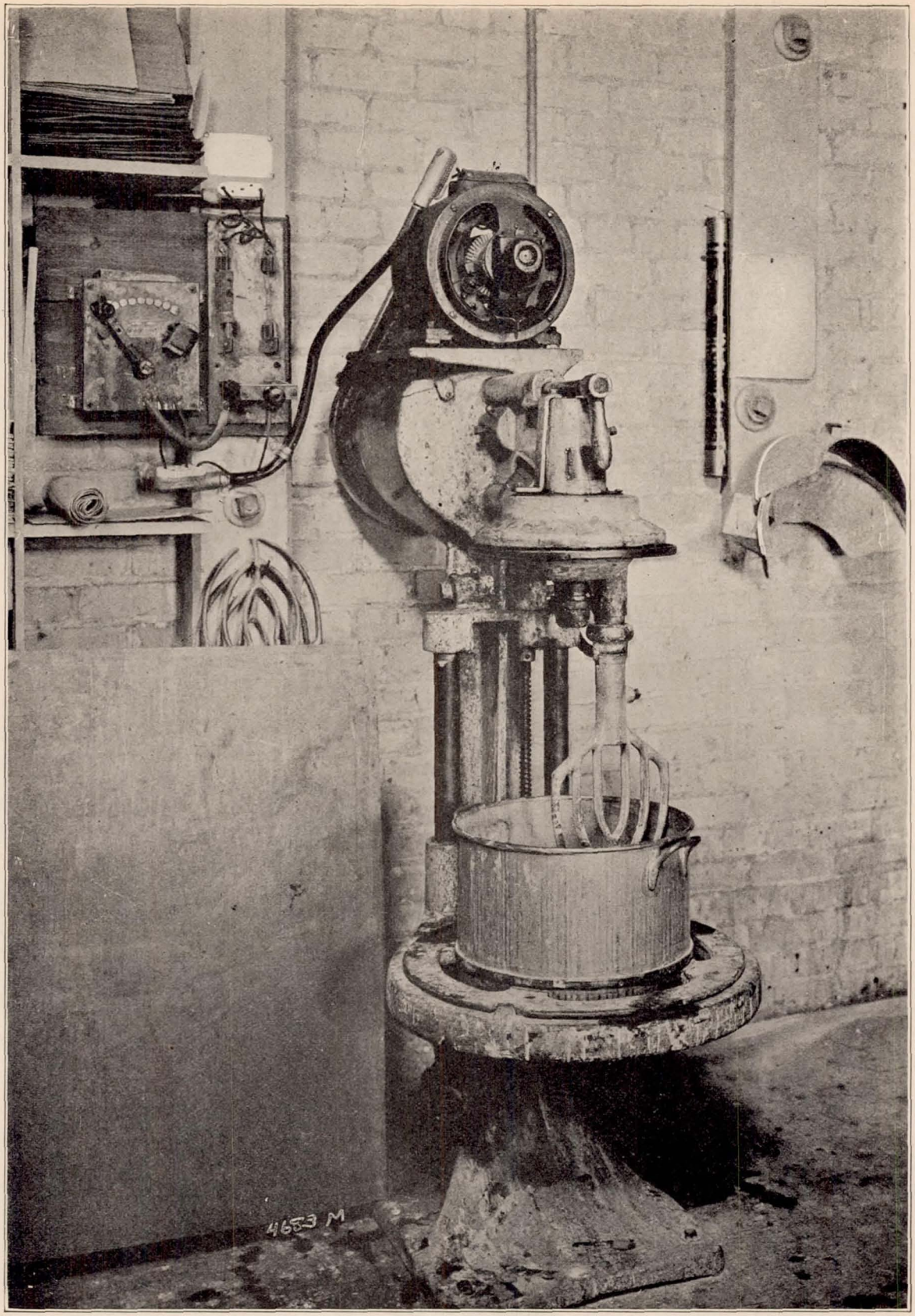


PLATE I.—TYPE OF CAKE AND EGG MIXER USED FOR MIXING CASEIN GLUE.

Specific gravity		1.38 to 1.42
Density (Baumé scale)		40.31° to 42.96°
Sodium oxide	per cent	9.38 to 9.88
Silica	do	31.41 to 32.38

This formula gives a glue of considerable water resistance. It has formed the basis for a large part of the later experimental work on casein glues at the Forest Products Laboratory. By modifying the proportions of materials and adding still other components glues of very desirable qualities are obtained. The degree of water-resistance and the workable life of the glue after mixing can be greatly varied. This property of the wet-mix glues, namely the variation of the components to attain glues of special qualities is one of the chief advantages over the dry-mix type. The dry-mix glues on the other hand require less technical knowledge on the part of the user than do the wet-mix type.

PREPARED CASEIN GLUES.

Commercial casein water-resistant glues are of the dry-mix type, of which four are at present on the market. They are made by secret formulas and the details of the method of their manufacture are not public. Directions for mixing these glues are furnished by the manufacturers and should generally be followed by the user. The principal points to be observed in the mixing of prepared casein glues are:

1. A thorough mixing of the dry glue from each or all containers before adding to the water. This is advisable on account of the segregation of ingredients of different specific gravities which may occur during shipment from the factory to the consuming plant. Sifting is not advisable, as it may remove from the glue some essential component.

2. Proportions of glue and water should always be weighed, not measured.

3. The glue should be added slowly to the water accompanied by vigorous agitation in order to avoid a lumpy mixture.

4. After the glue is well mixed into the water, the stirring should continue more slowly until all particles are thoroughly dissolved and the glue appears of a smooth, creamy consistency.

5. The desired consistency of the glue should be attained during the mixing and no attempt should be made to thin the glue should it become too thick in use. It should be mixed only as fast as it is being used.

The proportions of dry glue and water should, in general, be as directed by the manufacturer. However, the exact proportions will vary with (1) different glues, (2) different shipments of the same glue, and (3) the kind of work for which the glue is to be used. Only average proportions can be stipulated by the manufacturer; and the operator, in order to obtain satisfactory consistencies, may find it necessary at times to vary from the average proportions specified.

TYPE OF MIXER.

The ordinary types of mixers used for animal and vegetable glues are not well adapted to casein glues. The prime requisites for a mixer for these glues are: (1) Rapid agitation and, preferably, different speeds of the paddle; (2) a glue pot that can be readily cleaned—preferably one that can be detached from the machine itself; and (3) a glue pot of metal that will not corrode under the action of alkali. The mixing pot should not be of brass, copper, or aluminum, as the alkali usually present in casein glues will attack these metals. No provision need be made for heating, as casein glues must not be heated. A mixer that has proved satisfactory at the Forest Products Laboratory is a power cake-dough mixer of the type used by bakers. (See Plate I.) The machine has a double-acting paddle and may be operated at three different speeds. Some glue manufacturers have devised inexpensive machines which do good work and which embody the essential points of thorough agitation and ease of cleaning the mixing bowl.

APPLICATION OF GLUE.

Casein glue may be applied to the wood either by hand or with a machine spreader. In applying by hand, a wire brush or a metal scraper gives good results. If the glue is to be spread on irregular joints with a bristle brush a somewhat thinner mixture may have to be used. The ordinary corrugated roll type of machine spreader works well. Enough glue should be spread to cover both surfaces of the joint and a small amount should squeeze out from the joints when pressure is applied.

The working life of casein glues varies from a few to many hours. A glue of moderate consistency should have a life of at least four or five hours, and glues may be made which will last for many hours. The fitness of a glue for use should be judged by its consistency; ordinarily, as long as it can be uniformly spread, a good glue will give good results. The time that may elapse between the spreading of the glue upon the wood and the pressing will depend upon several factors, chief of which are: (1) The moisture content of the wood; (2) the consistency of the glue; (3) the kind of wood; (4) the quantity of glue applied, and (5) the temperature of the wood and glue. The time should be correspondingly reduced if the wood is of an open, porous nature and of a low moisture content, or if a thin spread or a thick, heavy glue is used. A high temperature causes the moisture to disappear more rapidly from the glue layer and also hastens the setting of the glue. In general, the pressure should be applied while the glue is yet in a wet condition, in order to obtain contact between the uncoated wood and the glue layer. If the glue becomes too thick, poor contact will result. In most cases, if pressure is applied within ten to fifteen minutes good results will be obtained. Under other conditions a longer time may elapse.

PRESSURE.

Sufficient pressure should be applied to bring the layers of wood into close contact with the glue. A pressure of from 75 to 100 pounds per square inch is usually considered ample. This will necessarily vary with the consistency of the glue and the character of the material being joined. Greater pressures are necessary for irregularly surfaced material and thick glue mixtures than with the opposite conditions. The time under pressure may vary from a half-hour to a much longer period. Good joints have been obtained by pressing for only one-half hour. A longer period will probably give better results. Where it is convenient retaining in clamps over night is generally practiced.

After the material is removed from the press, it should preferably be allowed to condition before being finished. The time required for conditioning will depend upon the size of the stock, the moisture content of the material before gluing, the condition under which it is seasoned and the requirements of the finished product. A uniform moisture content of approximately that desired in the finished piece should prevail in the material before it is put through the finishing process.

STORAGE OF CASEIN GLUES.

Dry casein and casein glues will keep for a long time if stored under proper conditions. When bought in large quantities they should be stored in a cool, dry place, as excessive moisture and high temperatures cause deterioration.

STRENGTH AND WATER-RESISTANCE.

Casein glues, when properly mixed and applied, have good strength and water-resistant properties. These qualities are well demonstrated by the tests imposed on plywood manufactured for use in airplanes. To be accepted samples were required to show no separation of the plies after boiling in water for eight hours or soaking in cold water for ten days. For shearing strength in plywood the requirements were at least 150 pounds per square inch, but most of the plywood tested at the Forest Products Laboratory showed values considerably higher than this minimum requirement. Tested wet after several days' soaking, casein glues

commonly have from 20 to 40 per cent of their dry plywood shear strength. If, however, the glue is redried after being soaked, the original strength of the glue is very largely recovered.

As a joint glue, casein is as strong as the wood of practically all of our common species. Tested on blocks of maple with the grain running in the same direction, shearing strengths are commonly obtained ranging from 2,000 to 2,500 pounds per square inch, with a large percentage of failures in the wood. The progress which is being made in developing new formulas and improving the methods of manufacture is constantly increasing the strength and water-resistance which can reasonably be demanded of casein glues.

REFERENCES ON CASEIN AND CASEIN GLUES.

BOOKS ON CHEMISTRY OF CASEIN.

The physical chemistry of the proteins. By T. B. Robertson. Pp. 483. Longmans, Green & Co., New York, 1918.

General characteristics of proteins. By S. B. Schryver. Pp. 86. Longmans, Green & Co., London, 1909.

Chemistry of the proteids. By Gustav Mann. Pp. 606. Macmillan & Co., London, 1906.

Chemical constitution of the proteids. By R. H. A. Plimmer. Pp. 165, illus. Longmans, Green & Co., New York, 1917.

Casein and its primary cleavage products. By R. H. Chittenden and H. M. Painter. In the transactions of the Connecticut Academy of Arts and Sciences, 1888, vol. 7, pp. 362–405.

Caseoses, casein, dyspeptone, and casein peptone. By R. H. Chittenden. In the transactions of the Connecticut Academy of Arts and Sciences, 1888, vol. 8, pp. 66–105.

Dairy chemistry. By H. D. Richmond. Pp. 434, illus. J. B. Lippincott Co., Philadelphia, Pa., 1914.

Commercial organic analysis. By A. H. Allen. 4 vols., illus. J. & A. Churchill, London, 1898–1907.

Dictionary of applied chemistry. By T. E. Thorpe. 5 vols., illus. Longmans, Green & Co., New York, 1912–13.

A textbook of physiological chemistry. By O. Hammarsten, translated by J. A. Mandel. Pp. 628. J. Wiley & Son, New York, 1900.

Practical physiological chemistry. By P. B. Hawk. Pp. 661, illus. P. Blackiston's Son & Co., Philadelphia, Pa., 1918.

Industrial chemistry. By A. Rogers and A. B. Aubert. Pp. 854, illus. D. Van Nostrand Co., New York, 1912.

Treatise on general and industrial inorganic chemistry. By Ettore Molinari. 3d Italian edition tr. by E. Feilmann. Pp. 704. P. Blackiston's Son & Co., Philadelphia, Pa., 1912.

Casein, its preparation and technical utilization. By R. Scherer. Pp. 182, illus. Scott Greenwood & Son, London, 1911.

The manufacture of casein from buttermilk or skim milk. By A. O. Dahlberg. Pp. 32, illus. U. S. Department of Agriculture Bulletin No. 661. U. S. Department of Agriculture, Washington, D. C., 1918.

Agglutinants of all kinds, for all purposes. By H. C. Standage. Pp. 267. D. Van Nostrand Co., New York, 1907. $3.50. Contains information on casein glues.

ARTICLES ON MANUFACTURE AND USE OF CASEIN.

Colloid chemistry of casein, etc. By H. B. Stocks. In Report of British Association for the Advancement of Science, pp. 65–97, 1917.

Casein, its utilization in the paper industry. In World's Paper Trade Review, vol. 46, pp. 281–657, 1906.

Casein and its applications. By Richardson. In the Journal of the Society of Dyers and Colorists. Vol. 25, p. 48, 1909.

Comments from Copenhagen; casein production. In New York Produce Review and American Creameries. Vol. 31, No. 1, p. 12, October 26, 1910.

PATENT LITERATURE ON CASEIN GLUES.

U. S. Patent 838785 Isaacs, 1906.
845790 Isaacs, 1907.
848746 Isaacs, 1907.
845791 Isaacs, 1907.
843277 Isaacs, 1907.
1192783 Isaacs, 1916.
183024 Ross.
21744 Gardner, 1896.
609200 Hall, 1896 (Reissue 11,811, 1900).
1291396 Butterman, 1918.
1310706 Lindauer, 1918.

German Patents 116355 Wenck, 1900.
154289 Jeromins, 1904.
60156 Pick, 1891.

A large number of articles have been published on the chemical properties of pure casein. They can be located through Chemical Abstracts. Most of the articles published in English have appeared in the following journals:

Journal of Biological Chemistry.
Journal of Physical Chemistry.
Journal of the American Chemical Society.
Technical Bulletins of the New York Agricultural Experiment Station.

BLOOD ALBUMIN GLUES—THEIR MANUFACTURE, PREPARATION AND APPLICATION.

The use of blood albumin glue is comparatively new in this country. Previous to our entry into the war, a few manufacturing plants had their own secret formulas and were using them in the preparation of glue. But the demand for water-resistant plywood for military purposes caused a marked increase in the production of all kinds of waterproof glues, both casein and blood albumin. During the period of the war, the Forest Products Laboratory developed several formulas for blood albumin glues and worked out a method of gluing very thin veneer by a dry blood glue process.

WET GLUE PROCESS.

Prepared blood albumin glues are not offered on the market, chiefly on account of the decrease in solubility of the albumin with age. They are, therefore, mixed at the time of using. The glue may be made either from the fresh blood of slaughtered animals or from black soluble blood albumin obtained by processing the fresh blood. To make the use of fresh blood feasible, the supply must be readily accessible to the place of manufacture, inasmuch as rapid decomposition takes place and renders it unsatisfactory for glue purposes. Unless utilized at once it must therefore be treated with a preservative or converted into a dried soluble form. The dried soluble albumin is the form from which the glue is generally made, and is obtained by subjecting the fresh blood to a process for removing the fibrin and part of the red corpuscles and then evaporating to dryness at a temperature below the coagulating point of the albumin, which is approximately 160° F.

PREPARATION OF GLUE.

(Forest Products Laboratory Method.)

In order to put the dried albumin into solution, it is necessary to allow it to soak for some time before stirring. It is advisable to add water at about room temperature to the albumin and allow it to stand two hours or more before stirring. It should then be agitated until it is of uniform consistency. If coarse particles of insoluble material occur, the mixture may be strained through a screen of about 30 meshes to the inch. The dried albumin always contains some insoluble material and becomes more and more insoluble with age.

A mixture of blood albumin and water makes a glue with a considerable degree of adhesiveness, but it may be improved by the addition of other materials. The basic blood albumin glue formula[1] for the wet glue process worked out at the Forest Products Laboratory consists of:

6 parts of black soluble blood albumin (90 per cent solubility).
11 parts of water at about 80° F.
¼ part of ammonium hydroxide (sp. gr. 0.90).
⅛ part hydrated lime (from 2 to 3 per cent of the weight of albumin).

After the blood has been put in solution, the ammonia is added while stirring the mixture slowly. The lime is then added in the form of a thick cream, and agitation should be continued slowly for a few minutes. Care should be exercised in the use of the lime, inasmuch as a small excess will cause the mixture to thicken and become a jellylike mass. The glue should be of

[1] Patent applied for in the name of S. B. Henning, Forest Products Laboratory.

moderate consistency when mixed and should be suitable for use for several hours. The exact proportions of albumin and water may be varied to produce a glue of greater or less consistency or to suit an albumin of different solubility than that specified.

APPLICATION OF GLUE.

The glue may be applied to the wood either with a bristle brush or with a glue spreader. If the spreader is used it should be run only when actually coating the wood, as otherwise the glue may become foamy.

PRESSING.

To set the glue, a minimum temperature of approximately 160° F. is necessary, which causes the blood to coagulate. When thoroughly coagulated, the glue can not again be dissolved in water. The heat is conveniently applied to the wood by pressing between the hot platens of a hydraulic press. In order to reduce the time required in the press and thus increase its capacity, it is customary to use a temperature of from 200 to 220° F. Excessively high temperatures, however, turn the moisture in the glue and wood to steam and are likely to produce steam pockets or blisters between the plies of wood. A pressure of from 50 to 100 pounds per square inch is desirable. The time required for pressing depends upon the thickness of the plies, the number of panels in the press, and the temperature of the plates. With a temperature of 212° F. three minutes are sufficient for one three-ply panel with $\frac{1}{16}$-inch face plies. The necessary length of time naturally increases with an increase in thickness of material.

Blood albumin glue is used in plywood construction chiefly. It may, however, be used for thicker material. For thick blocks it is necessary to apply pressure and maintain it by the use of retaining clamps, and then subject the material in a kiln or hot room to a temperature sufficient to set the glue.

Blood albumin glue is highly water-resistant, surpassing in this respect the present casein glues. It retains its shearing strength to a remarkable degree after soaking or boiling, giving from 50 to 75 per cent of the dry strength. It is known to possess strength sufficient for joint work, although, on account of the difficulty of setting the glue, it is generally considered impractical for this purpose.

PRECAUTIONS IN THE USE OF BLOOD ALBUMIN GLUE.

Several precautions should be observed in mixing and applying blood albumin glue.

1. Weigh out all constituents; do not measure them.
2. Add cold water to blood albumin and do not heat mixture.
3. Do not stir blood until it has soaked for from one to two hours.
4. Avoid excessive stirring of the glue or agitation on the spreader, since this produces foamy glue.
5. Load press and apply pressure quickly to prevent coagulating the blood before pressure is secured.
6. Pressures ranging from 50 to 100 pounds per square inch are advisable, depending upon the glue consistency, nature of wood, etc.
7. Excessively high temperatures of the platens of the press produce steam, causing blisters. A range of 200 to 212° F. is advisable.
8. Panels should be left in the press until the heat has penetrated so as to raise all parts to at least 160° F.
9. Be careful not to use an excessive amount of lime or a strongly alkaline water.

DRY GLUE PROCESS FOR THIN VENEER.

Gluing thin veneer ranging from $\frac{1}{30}$ to $\frac{1}{125}$ of an inch into a very thin panel has always been extremely difficult. The principal causes of trouble have been penetration of glue through the face plies and excessive swelling of the thin veneer due to the rapid absorption of water

from the wet glue, producing overlaps, curling, and wrinkling. These troubles have made the manufacture of very thin plywood a very difficult and expensive process. To overcome these difficulties, a method of gluing very thin veneer was worked out at the Forest Products Laboratory in cooperation with the Bureau of Aircraft Production for the construction of experimental material, particularly for airplane wing covering.

A blood albumin glue was developed which when dried could be used successfully to glue veneer $\frac{1}{125}$ of an inch in thickness, or even thinner. The glue mixture used in this process varies from the standard formula given above principally in the addition of a substance which makes the glue hygroscopic, or capable of attracting and retaining moisture, sufficiently to give a contact with wood.

PREPARATION OF GLUE LAYER.

The principal steps in the manufacture of the glue layer are: (1) Mixing the glue, (2) coating on tissue paper or cloth, and (3) drying.

To obtain good results, the glue must be mixed thin and be free from lumps or undissolved particles. Straining through a sieve is absolutely necessary in this case.

The first machine used for coating this glue on the paper and drying was devised and built at the Forest Products Laboratory. The process was later introduced into a commercial paper coating plant, an improved form of the machine for drying and coating was installed, and the product can now be produced on a commercial basis.

A thin, porous tissue paper is used for coating and is placed in a machine geared to run it through the glue bath at a rate of approximately 1 foot per minute. The tissue paper passes over a roller in the glue bath, and upward into a drying chamber to a worm roller upon which there are strips of felt to prevent it from wrinkling. It then passes over a third roller and through pinch rolls to a final dry roll. Cloth may be used as the medium upon which the glue is dried and then be made to serve as one ply in panel construction.

GLUING PROCESS.

In manufacturing plywood with the glue, sheets of it are placed between the plies of the wood and pressed in a hot press. A pressure of from 150 to 200 pounds per square inch is necessary in order to bring about good contact between the glue layer and the wood. If the moisture of the veneer is low, the water-resistant properties of the plywood may be increased by a slight sprinkling or sponging of the veneer immediately before placing in the press.

ADVANTAGES OF THIS PROCESS.

This form of glue has advantages over the wet glue process, chief of which are:

1. Veneer as thin as one-one hundred and twenty-fifth of an inch may be glued up successfully.
2. Overlaps, wrinkling, open joints, etc., are overcome.
3. Gluing with the addition of little or no moisture overcomes cupping and twisting of panels.
4. Drying of plywood is largely eliminated.
5. Subsequent trouble in checking of veneer in drying is eliminated.
6. Glue is always ready for use and keeps for a long time.
7. It can probably be used more rapidly and with less labor than the wet glue process.
8. No spreader is required.

VEGETABLE GLUE—MANUFACTURE AND USE.

The term vegetable glue is considered in the woodworking industries to mean glue made from starch. There are other adhesives which are derived from vegetable sources, but these are not commonly used in woodworking. Vegetable glue is usually made from cassava starch.

which appears to be especially adapted for the purposes, but others such as corn starch or potato starch are sometimes used alone or mixed with cassava starch. Vegetable glue is not used in airplane manufacture but is here discussed briefly as a matter of interest.

In one of the vegetable glues now on the market, the cassava starch is first treated to reduce its water absorbing power. This is ordinarily accomplished by heating the starch with an equal weight of water to 130° F., stirring, and then adding strong sulphuric acid to the mixture. Stirring is then continued for several hours after which the acid is neutralized with an alkali and the mixture finally drained and dried. It is sold in this form as a starch base for the preparation of vegetable glue by the addition of caustic soda. It is customary for the manufacturer to sell the starch base and the caustic on the basis of a definite price per pound for "dry glue."

In preparing the glue for use, the starch is usually placed in a jacketed mixer so that it can be heated and stirred when the water and caustic soda are added. About one hour's stirring is necessary to complete the mixing. The glue can be prepared without heat if a higher percentage of caustic is used.

The resulting product is a viscous, translucent material which is used cold and which will keep for many days without deterioration. On account of its stiff consistency mechanical spreaders are required to apply the glue. It has not been found suitable, therefore, for irregularly shaped joints, which require hand spreading. It is pressed in cold presses in the same manner as casein glue.

There are other prepared vegetable glues on the market which, up to the present time have not been so widely used as the one just discussed. These have various starches for their bases and are manufactured by processes which are more or less secret. It is also possible to make vegetable glue of good strength directly from the unprepared starch, with or without the use of caustic soda or other chemicals.

This method and the methods which vary the amount of caustic used promise to be of value in eliminating the objection to vegetable glue occasioned by staining, which often occurs in gluing fancy furniture veneers, such as one-twenty-eighth inch birdseye maple and mahogany. The reduction of the amount of alkali in the glue will reduce the danger of staining, but will shorten the life. A vegetable glue made in this way without caustic will, however, remain workable for 24 hours.

The status of the various vegetable glues is more or less involved in patent litigation, and in using any of them the user should be thoroughly informed on this phase of the subject.

COMPARISON OF VARIOUS TYPES OF GLUE.

Each of the five types of glue, namely, animal, casein, vegetable, blood, and liquid, has its own peculiarities, properties, and uses which influence its suitability for various purposes.

Animal glue has been used so long and is so familiar to woodworkers that the value of other glues is measured by comparing with animal glue. The principal desirable properties of animal glue are the great strength and reliability of the higher grades, its free-flowing consistency, and the fact that it does not cause staining of fancy veneers. So far no glue has been found by the woodworking industry to be as suitable as animal glue for hand spreading on irregularly shaped joints, although a cheaper glue would be very desirable. The price of animal glue and the fact that it is not highly water resistant are the chief factors which limit its use.

Casein glue has been used commercially for such a short time that its possibilities and limitations are not well known. It has good strength, is used cold, and can be spread with a brush, all of which are desirable properties. The property most featured, however, is its high water resistance, which makes it suitable for gluing articles to be used under moist conditions. This property makes it a very desirable glue for special purposes.

Among the disadvantages of casein glues are their tendency to stain thin veneer and the relatively short working life of some kinds. They are also said to be somewhat harder on tools than animal and vegetable glues. This may be overcome possibly by using different steel in the tools, or perhaps by altering formulas.

Casein glues by proper manipulation can be given certain special properties, as desired. Their water resistance, strength, consistency, spread, and cost can be varied over wide ranges by one thoroughly familiar with the subject. This is true to a much greater extent of the wet than of the prepared casein glues. Already considerable reductions in cost have been made in both kinds, but particularly in the wet glues. It seems quite probable that casein glues will some day be serious competitors of vegetable glues on a price basis, without regard to water resistance or other properties. Already they are entering the field of animal glue in joint work. The fact that they can be made to spread readily by hand on irregular joints is in their favor in this connection, in addition to their lower price.

Vegetable glues have found wide use in recent years chiefly on account of their cheapness. Other valuable features are that they are used cold, and that they remain in good working condition and free from decomposition for many days. They are extremely viscous, however, and it is not practicable to spread them by hand. Their lack of water resistance and the fact that they usually cause staining in thin fancy veneer are factors limiting their use.

Experimental work by manufacturers is constantly under way with the object of developing new and better grades of vegetable glue, and some progress has been made toward producing a stainless grade. The future developments in this line depend to some extent upon decisions in patent litigation.

Blood albumin glue has shown notably high resistance to moisture, especially in the boiling test. This makes it particularly suitable for gluing plywood which is later to be softened in hot water and molded. The production of molded plywood articles has been very limited, but it offers a good field for future development.

Blood glue formulas can be altered so as to produce glues of various properties. It is possible to make some very cheap blood glues suitable for the production of medium or cheap grade articles. A very valuable form in which it can be made is the dry glue tissue. This promises to be valuable for laying fancy veneers, since by its use it is possible to eliminate much of the trouble due to moisture changes. The factors limiting the use of blood glue are the expensive apparatus required, the relatively low production per press, and the fact that it is not very practical for gluing thick stock.

Liquid glues are, in general, similar in properties to animal glue. Some brands are quite equal in strength to good joint glues, but other brands are very weak and unreliable. Their great advantage is that they come in prepared form, ready for immediate use. This makes them particularly suitable for patch work and small gluing jobs. The factors which limit their use are their high price, their lack of water resistance, and the difficulty the manufacturer has in distinguishing between good brands and poor brands.

The following table gives in summarized form a comparison of the various glues. From the table and the preceding discussion it will be seen that there is no glue which is superior in all respects to all the others.

Comparison of various glues.

Particular compared.	Animal glue.	Casein glue.	Vegetable glue.	Blood glue.	Liquid glue.
Source.	Animal hides, bones, etc.	Casein from milk.	Starch—generally cassava.	Soluble dried blood.	Animal glue, or skins, bones, etc., of fish.
Cost per pound (Apr., 1919); (veneer glue prices for carload lots).	High grade, 25 to 42 cents per pound; veneer grades, 15 to 30 cents per pound.	Casein, 14 to 18 cents per pound; prepared casein glues, 16 to 20 cents per pound.	Prepared glue, 10 to 12 cents per pound; starch, 8 to 9 cents per pound.	Dried blood, about 20 cents per pound.	$1 to $5 per gallon.
Spread[1]— Extremes reported: Common range:	20 to 45. 25 to 35.	30 to 80. 35 to 55.	35 to 70. 35 to 50.	30 to 100.	No data.
Mixing.	Soaked in water, then melted.	Mixed cold, with rapid stirring.	Mixed with alkali and water, with or without heat; can be made without alkali.	Mixed cold.	Requires no preparation.
Application.	Applied warm with brush or mechanical spreader.	Applied cold with brush or mechanical spreader.	Applied cold with mechanical spreader.	Applied cold by hand or with mechanical spreader.	Applied cold or warm, usually by hand.
Temperature of press.	Cold; hot cauls frequently used.	Cold.	Cold.	Hot.	Cold.
Strength (block shear test).	High grade equal in shear strength to strongest American woods; medium grades slightly lower.	Similar to medium-grade animal glue.	Similar to or slightly less than medium-grade animal glue.	Similar to or slightly less than medium-grade animal glue.	Good grades similar to medium-grade animal glue; some brands very weak.
Water resistance.	Low.	High.	Low.	High.	Low.
Staining.	Does not stain.	Stains thin veneer of some species.	If mixed with caustic soda, stains thin veneer of some species.	Does not stain, but the glue is very dark; dry process glue does not show through.	Does not stain.
Uses in woodworking.	High grade, where a strong joint is desired; low grade, sometimes used for veneering, especially where it is desired to prevent staining.	Mainly where water resistance is desired in veneered or joint work.	Mainly in veneered work on account of cheapness, but also somewhat for joint work.	Almost entirely for water-resistant plywood for aircraft purposes and for articles to be molded after boiling in water.	Mainly for repair work and gluing small articles by hand.

[1] Expressed in square feet of glue line per pound of dry glue for veneer work.

TESTING GLUES.

The tests used in judging glue vary with the types. Strength tests are suitable for all types. Water-resistance tests are made on casein and blood glues. Additional tests made on animal glues are with respect to viscosity, jelly strength, odor, keeping qualities, grease, foam, and reaction to litmus. Chemical analysis is generally of little value in judging glue.

STRENGTH.

BLOCK SHEAR TEST.

Strength tests are made by gluing together two or more pieces of wood and noting the pressure or pull required to break them apart. A number of methods of making the test specimens and breaking them have been devised. These depend to a certain extent upon the character of work expected of the glue and the nature of the testing apparatus available. In the experiments at the Forest Products Laboratory the simplest and most convenient method found for testing the strength of the glue is a shear test.

Two blocks of selected hard maple, about 1 by 2½ by 12 inches in size, are glued together. After the glue has aged sufficiently they are cut into shear specimens as shown in figure 1. These are placed in a testing machine so that the base of the long half of the block rests on

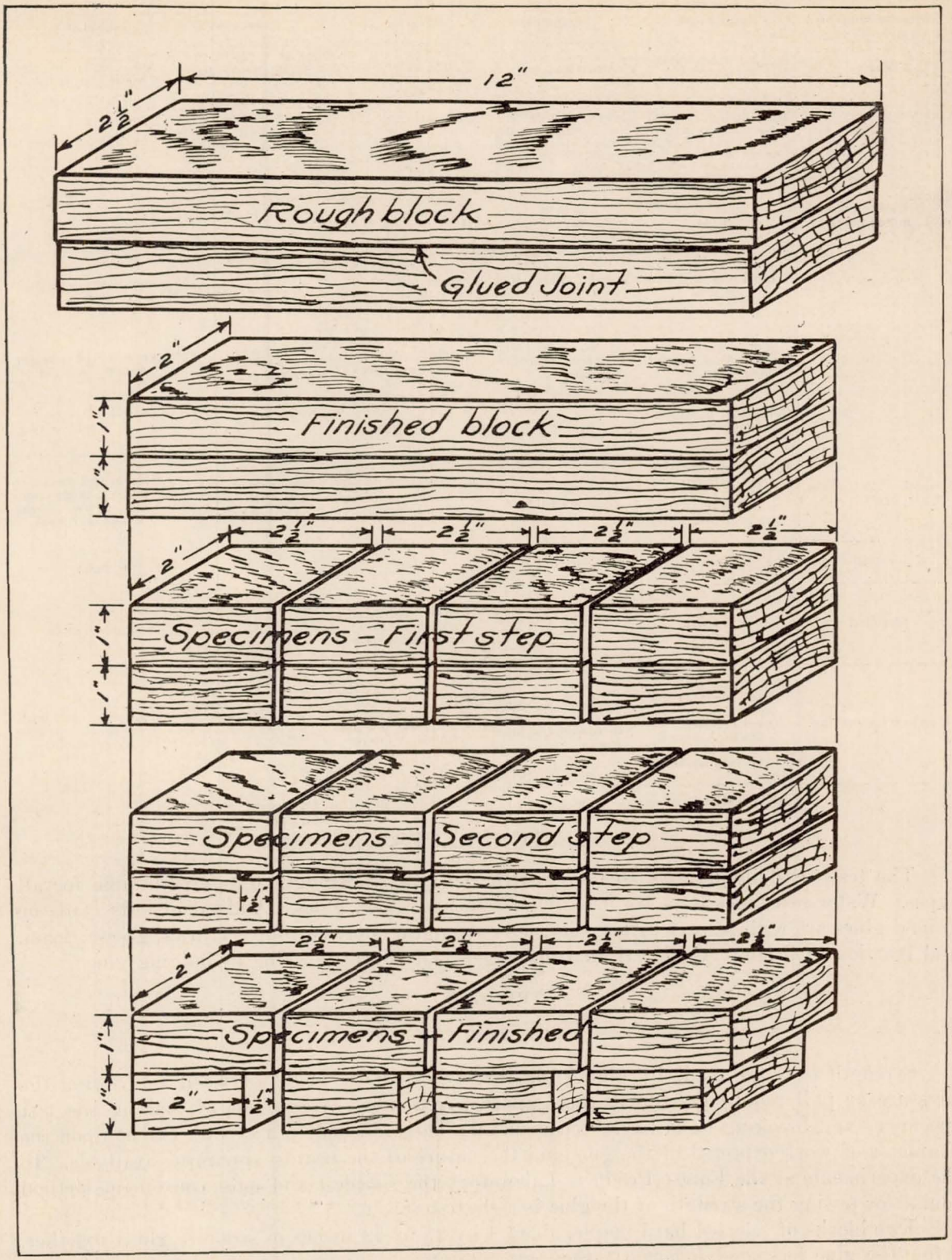


FIG. 1.—Method of preparing specimens for glue strength tests.

a metal seat. (See fig. 2–C.). Pressure is then exerted on the short half, causing it to slide past the long half at the glued joint. The pressure required to separate the blocks in this way is measured and the percentage of the area of wood surface torn out by the glue estimated.

If the failure occurs entirely in the glue, a measure of the strength of the glued joint is obtained, but if the failure is entirely or partly in the wood, as frequently happens, the full strength of the glue is not developed, and the test may have to be repeated using stronger blocks.

The same method has been used in securing data on the strength of wood in shear. Consequently when the strength of glue has been determined it can be compared with that of any wood whose average shearing strength is known.

Four specimens are usually broken and an average taken of their individual values. The variation in the values can be kept at a minimum if the specimens are selected, prepared, and tested under as nearly the same conditions as possible. A very important factor is the selection

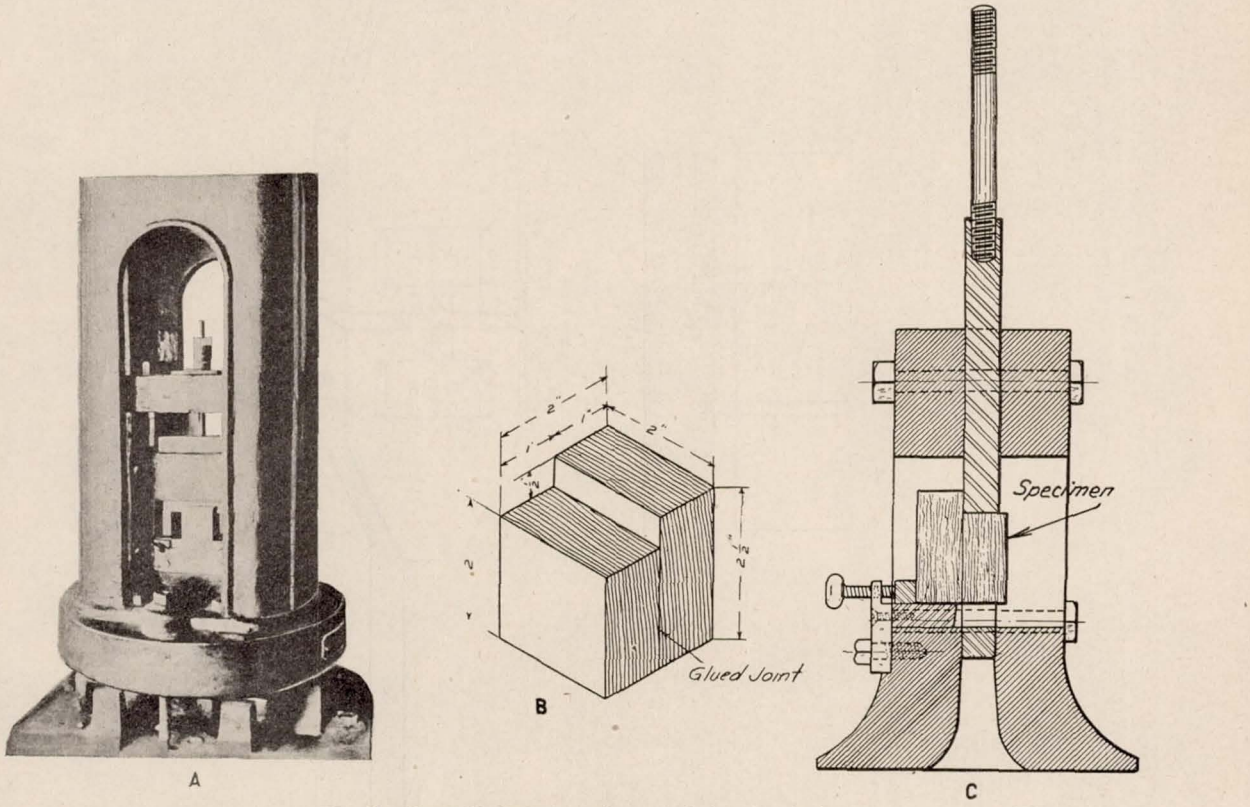


FIG. 2.—Shear block test specimen and shearing tool.

of the wood. The species should be the one upon which it is proposed to use the glue, or one at least equally strong. Hard maple is the standard wood in use at the Forest Products Laboratory. Other woods of equal or greater strength which might be used are sweet birch, black locust, flowering dogwood, canyon live oak, persimmon, big shellbark hickory, and western yew.

It is a good plan to test hide glue at three or four different dilutions. Four different sets of specimens should therefore be prepared, using 2, $2\frac{1}{4}$, $2\frac{1}{2}$, and $2\frac{3}{4}$ parts water, respectively, to one part of glue. An exceedingly high-grade glue may work best at three to one, and there are low grades which will give best results with less than two parts of water to one of glue. Other types of glue should also be tested under conditions which will permit them to develop their full strength.

On account of the variable nature of wood and the impossibility of doing perfect gluing, the test is far from perfect as an absolute measure of the strength of a glue, but no other

strength test has been found to be nearly so good. It merely gives an idea of the ability of the glue to hold wood together. If only one or two specimens are tested, the results are apt to vary widely and be misleading, so it is desirable to base conclusions upon data from a considerable number of tests.

As a means of judging whether the glue is being used to the best advantage, the shear block test is very valuable. The specimens can be prepared from almost any piece of glued work, provided the laminations are not thinner than about one-fourth of an inch and the grain in adjacent laminations runs parallel. It is preferable that the specimens be cut to the size shown in figure 2, but it is not absolutely necessary; smaller sizes can be used if conditions require.

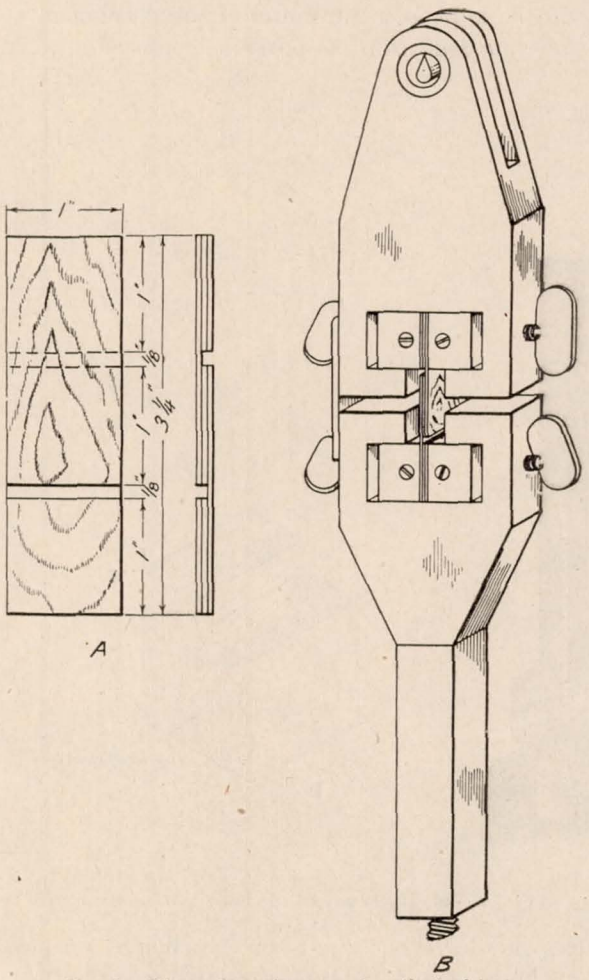


FIG. 3.—Plywood specimens and method of test.

PLYWOOD SHEAR TEST.

An additional strength test is made on glues used for the manufacture of plywood. This consists of shearing the plies apart. The form of specimen used at the Forest Products Laboratory is the one used during the war by the British and American Governments in testing aircraft plywood, and is shown in fig. 3–A. It is simple, easily prepared from any plywood panel and quickly tested. The machine used in the test is the type designed for testing cement, but is provided with special grips as shown in fig. 3–B. The specimen is placed under tension and fails principally from shearing. The shape of the specimen makes it impossible to develop the full shearing strength, but the test gives comparable results and serves to keep a close check on the uniformity of the product.

WATER RESISTANCE.

So-called waterproof glues may be tested by soaking or boiling specimens of plywood glued with them. The specimens used at the Forest Products Laboratory are 5 by 5 inches in size. The specimens are soaked for 10 days or boiled for eight hours and the results tabu-

FOREST PRODUCTS LABORATORY
FOREST SERVICE
UNITED STATES DEPARTMENT OF AGRICULTURE
MADISON, WISCONSIN

PLYWOOD INSPECTION TESTS

REPORT NO. 100

SAMPLE SUBMITTED BY Senior Inspector Richard Roe

MANUFACTURED BY X. Y. Z Co., AT Panelville, Ill.

DATE SAMPLE RECEIVED AT LABORATORY Nov. 16, 1918 TESTED BY John Doe DATE RESULTS REPORTED Nov. 26, 1918

DATE TEST STARTED	PANEL NO	DESCRIPTION OF PANELS: No. of Plies	Glue	Faces	Core	Boiling eight hours	Soaking ten days	RESULTS OF TESTS: Plywood Glue Shearing: Strength in Lbs. per Square Inch	Nature of Failure: Glue	Faces	Core	REMARKS	
I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XII	
		Prepared											
Nov.16	300-1	5	X	1/20 Birch	1/20 Poplar	B	C	233	✓		✓	206	1/4
	2	3	"	1/28 Mahog.	" "	B	A	256	✓	✓		207	1/8
	3	3	"	1/32 Mahog.	" "	B	B	229		✓		209	3/32
	4	3	"	" "	" "	A	A	238	✓	✓		208	3/32
	5	3	"	" "	1/28 Poplar	A	B	299	✓	✓		193	3/32
		Prepared											
	6	3	Y	" "	" "	A	B	331	✓	✓		194	3/32
	7	3	"	" "	" "	A	A	315	✓	✓		195	3/32
	8	3	"	1/20 "	1/16 Poplar	A	A	324	✓		✓	198	5/32
	9	3	"	1/32 "	1/28 "	A	A	318	✓	✓		199	3/32
	10	3	"	" "	1/28 "	A	B	321	✓	✓		200	3/32
	11	3	"	" "	1/28 "	A	A	302	✓	✓		201	3/32
	12	3	"	" "	1/28 "	A	A	329	✓	✓		202	3/32

REPORTED BY A.B.C. REPORT CHECKED BY G.L.M. APPROVED BY P.L.Y.

LEGEND

A. Indicates no separation of the plies.

B. Indicates that the total separation between all the plies, regardless of the number of plies, is not greater than ten per cent of the area of the sample tested.

C. Indicates a total separation greater than ten per cent and not more than fifty per cent of the area of the sample tested or indicates blisters or other manufacturing defects of such nature as would warrant further tests.

D. Indicates a total separation of over fifty per cent of the area of the sample tested.

W. F. These letters are included in the strength column where the specimens fail entirely in the wood and below 150 pounds per square inch.

T. T. Indicates that the specimens break when being sawed or the faces are too thin to test.

A check mark under the heading glue, faces, or core indicates where the failure took place. A glue failure indicates that the strength of the joint has been reached. In case the face or core fails, it is known that the joint is at least as strong as the figure recorded.

Inspector's description such as lot numbers, etc., are included in "Remarks" column.

FIG. 4.—Form for reporting routine plywood tests, filled out with actual figures from typical test.

lated on the form shown on fig. 4. The latter test, while not designed to duplicate any actual service condition, amounts to an accelerated soaking test and furnishes comparable results in a short time. If a more accurate test of water resistance is desired, plywood shear specimens may be cut, then boiled or soaked, and tested in the usual way in the plywood testing machine.

VISCOSITY.

The viscosity of animal glue is determined by allowing a specified amount of the glue at a definite temperature (usually 140° F.) to flow through a standard orifice. The time required is a measure of the viscosity. The time required for water to flow through is taken as the standard. In general, it is found that a glue with high viscosity is stronger than one of low viscosity and will take more water, although there are exceptions. Hide glues, as a rule, have higher viscosities than bone glues. A number of viscosimeters of different shapes have been devised. In the glue manufacturer's laboratory, where many tests must be made each day, an instrument must be used which will give results quickly. This can be done with a pipette, cut off at one end, or with a straight glass tube contracted at one end. These instruments are not always so arranged that the temperature of the glue within them can be controlled, and for a number of other reasons they are not entirely accurate. For better control of temperature and greater accuracy the Engler viscosimeter is often used. This is more complicated and more expensive than the glass tubes, and also slower to operate, but it has the advantage, in addition to greater accuracy, of being an instrument which is in general use for testing many kinds of materials. The values obtained by its use are readily understood by laboratory men and can be readily checked. The instrument can be purchased standardized and ready for use.

JELLY STRENGTH.

The term jelly strength refers to the firmness or elasticity of the jelly formed by cooling a glue solution of specified strength. Strong animal glues usually have high jelly strength. There is no standard instrument for determining it, and no standard unit for expressing it. In some laboratories the pressure required to break the surface of the jelly is measured. In others the depth is observed to which a weight of special shape will sink. Sometimes the jelly is cast in a conical shape and the weight required to press the point of the cone a certain distance is taken. The Smith jelly tester, which is sometimes used, is so constructed as to measure the pressure required to expand a rubber diaphragm into the jelly to a certain volume. This instrument is generally considered too inconvenient and slow, but it enables an accurate comparison to be made and is used by some testing laboratories. A very common test is the finger test, in which the relative strength of two or more jellies is compared by pressing the jelly with the fingers.

In making the jelly-strength test with any apparatus it is important that the conditions be very carefully controlled in order that comparable results may be obtained. The width and depth of the glue jelly should be as great as practicable, in order to reduce to a minimum the reinforcing effect of the bottom and sides of the vessel upon the resistance of the jelly to indentation. Once a standard is adopted it should be adhered to if comparative results are desired. The temperature of the jelly when tested is particularly important, as the relative strength of a number of jellies is not always the same at different temperatures. In other words, the jelly strength of different glues is not affected to the same extent by changes in temperature. The ideal way would be to cool and test the jellies in a room constantly maintained at the proper temperature. This is seldom practicable, however, and the jellies are generally cooled in a refrigerator and tested in a warmer room. In such cases it is important that the test be made as quickly as possible after removing the jelly from the refrigerator, so that the temperature will be practically the same as it was in the refrigerator. The strength of the glue solution must also be always the same, once a standard is adopted. Weaker solutions can be used for high-strength glues than for low-strength glues.

ODOR.

The odor of animal glue gives some indication of its source and its condition. Glue which has an offensive odor is not considered of the highest grade. The bad odor may be due to the use of partly decomposed stock, or to decay of the glue itself. For high-grade work it is

usually specified that the glue be sweet; that is, it must not have an offensive odor, which is determined by smelling a hot solution of the glue. The odor of different glues varies considerably, and it is difficult or impossible to express the different "shades." It is usually not difficult, however, to determine whether or not the odor is clean, or, as it is commonly called, sweet. The temperature and strength of solution are usually not specified.

KEEPING QUALITY.

The keeping quality of a glue is determined by allowing the jelly left from the jelly-strength test to stand in the laboratory at room temperature for a number of days. The odor and condition of the glue are noted at intervals. Glues with good keeping qualities will stand several days without developing an offensive odor, or showing any appearance of decomposition. A more rigorous test frequently adopted is to keep the solution in a thermostat at about 35° C. The glue should remain sweet at least 48 hours under these conditions.

GREASE.

For joint work a small amount of grease in glue is not a serious objection. Too much grease, however, is objectionable, as grease has no adhesive properties. For some classes of work, such as paper sizing, even a very small amount of grease can not be tolerated, as it gives the paper an objectional appearance. When glue is to be used in a spreader where foaming is likely to occur, a small amount of grease is desirable, as it retards foaming. The grease can be determined by chemical means if desired, but this is not necessary unless the exact amount of grease must be determined. The common method of testing for grease is to mix a little dye with the glue solution and paint it upon a piece of unsized white paper. If grease is present, the painted streak will have a mottled or spotted appearance. If there is no grease, the streak will be uniform.

FOAM.

Glue which foams badly is objectionable because air bubbles get into the joint and thus reduce the area in which the glue is in contact with both faces. Foamy glue is especially undesirable for use in gluing machines, as the glue is agitated much more than when it is used by hand, and the danger of incorporating air bubbles is greater. The amount of foam is determined by beating the glue solution for a specified time with an egg beater or similar instrument and then noting the height to which the foam rises and the quickness with which it subsides. All laboratories do not make the test in exactly the same way, but in any laboratory after a method has once been adopted it should be strictly followed. The foam test is generally made on the solution used in the viscosity test.

REACTION TO LITMUS.

By its reaction to litmus a glue shows whether it is acid, alkaline, or neutral. The test is made by dipping strips of red and blue litmus paper in the glue solution remaining after the viscosity test or some other test, and noting the color change. An acid glue turns blue litmus red, an alkaline glue turns red litmus blue, and a neutral glue will not change the color of either red or blue litmus. A glue containing a slight amount of acid is slightly preferable to one which is neutral or alkaline, because it is not quite so favorable a medium for the growth of the organisms which cause decay.

COMPARISON WITH STANDARD SAMPLE.

It is apparent that, for the most part, the tests for animal glues give comparative rather than absolute results. It is frequently difficult to compare the results of tests made by one laboratory with those made by another, as the strength of solution, temperature, and manipulation so often are different. For this reason, it is considered that the most satisfactory method

of purchasing animal glues is to specify that they shall be equal to a standard sample furnished the bidder to test in any way he sees fit. The bidder should also be informed as to the methods the purchaser intends to use in testing glue submitted to him as equal to the standard sample.

In using strength tests it should be remembered that there is a difference between testing the glue itself and testing the workmanship of the gluing. In the former a wood which will not fail before the glue fails should be used. If the glue is too strong the ideal testing wood is hard to find, but hard maple approaches the desired standard. In the latter it is only necessary to use the particular wood which will be glued in practice or some other wood equally strong. Then if the glue proves stronger than the wood, the test is satisfactory.

While in some cases equipment for strength tests would pay a large manufacturer, for smaller plants the cost is prohibitive. A system of inspection and certification for glues of various grades, such as was operated in connection with the control of glue purchased for aircraft manufacture during the war, would enable purchasers to secure glue of known quality without testing it themselves. Under this system glue was barreled, sealed, and certified at the plants on the basis of actual tests made at a central testing laboratory by glue experts. This system might be duplicated during peace times by the organization of an inspection service supported by an association of the glue-using industries.

REPORT No. 67

SUPPLIES AND PRODUCTION OF AIRCRAFT WOODS

COMPILED BY

W. N. SPARHAWK, Forest Examiner, Forest Service

U. S. Department of Agriculture

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REPORT No. 67.

SUPPLIES AND PRODUCTION OF AIRCRAFT WOODS.

By W. N. Sparhawk.

INTRODUCTORY.

The purpose of this report is to present in brief form such information as is available regarding the supplies of the kinds of wood that have been used or seem likely to become important in the construction of airplanes, and the amount of lumber of each species normally put on the market each year. A general statement is given of the uses to which each kind of wood is or may be put, but no attempt has been made to go into a technical discussion of these various uses.

The information herein contained has been compiled from a great many sources, including principally published and unpublished reports by various members of the Forest Service. Many of the figures given, particularly those relating to amounts of standing timber, are only crude estimates, but until we have a census of the forest resources of the country we shall have to depend largely on guesswork. The figures on production of lumber are taken from the annual lumber census reports and may be relied upon. Estimates as to the proportions of the total lumber production of different species that may be suitable for the manufacture of aircraft are necessarily very general, and are open to modification as methods of sawing or as airplane specifications change.

It is believed that all the species used to any extent or approved for use in American aircraft are included. However, specifications in all probability will be changed as the industry develops. Consequently, the use of many kinds of woods not now considered suitable may eventually be allowed.

Statements regarding the uses of the different woods are included in order to give an idea of the industries with which aircraft manufacturers will have to compete for their lumber supplies. The figures published were obtained several years ago and hence may not exactly represent present conditions, since the annual production of lumber of many of the species has changed considerably in the interval.

The maps that accompany the text show by dots the approximate locations of the mills that in 1917 produced the largest amounts of the lumber of most of the species covered. These maps, therefore, indicate in a general way the sources of commercial supplies of the various species.

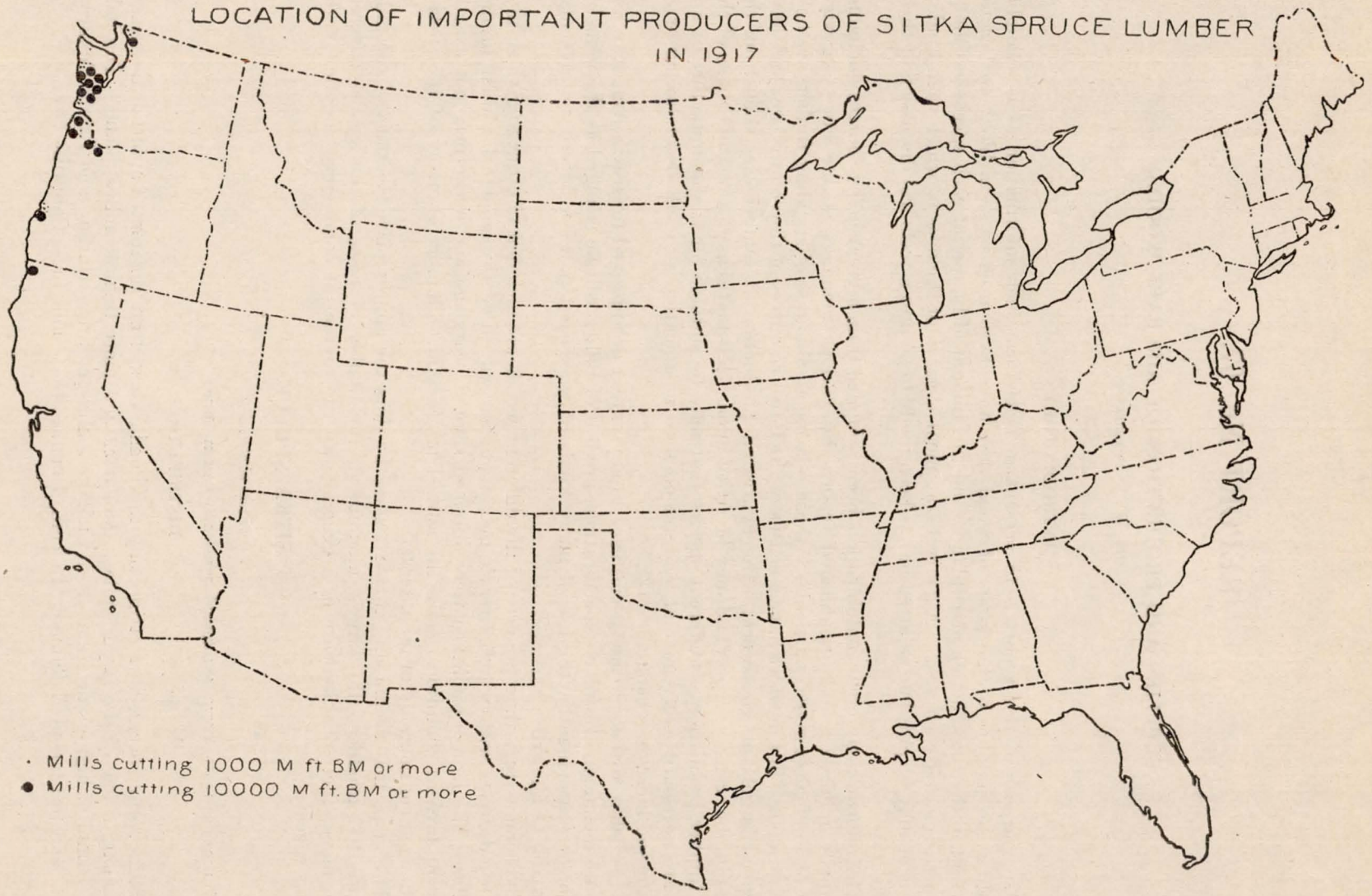
SITKA SPRUCE.

(Picea sitchensis.)

This species is also known as tideland spruce and western spruce.

DISTRIBUTION.

Sitka spruce occurs in a strip along the Pacific coast from northern California to Alaska. Only along a few of the larger valleys does it extend more than 40 miles inland. The bulk of the stand of high-grade spruce is in Clallam, Jefferson, Grays Harbor, and Pacific Counties, Wash., and in Clatsop, Tillamook, Lincoln, Douglas, Coos, and Lane Counties, Oreg.


LOCATION OF IMPORTANT PRODUCERS OF SITKA SPRUCE LUMBER
IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 10000 M ft. BM or more

MAP No. 1

USE IN AIRCRAFT.

Spruce is the wood par excellence for the construction of aircraft. It is light and has greater strength than other woods of similar weight. It is stiff, has a considerable degree of toughness, and can be worked with ease. These properties have made it the most generally used wood for wing beams and struts, and large quantities are employed for longerons, ribs, and plywood. Although there is no great difference in the strength properties of red, white, and Sitka spruce, the latter species on account of its greater size and consequently its larger proportion of clear lumber, is a more important source of aircraft material than the other two. Because of this and the large supplies of virgin timber still remaining, Sitka spruce will probably for many years be a very important species in the aircraft industry, notwithstanding the fact that the supply is so far away from centers of manufacture.

SUPPLY OF TIMBER.

Sitka spruce does not occur in pure stands over considerable areas, but grows in mixture with Douglas fir, western hemlock, grand fir, western red cedar, and associated species. It constitutes from 12 to 40 per cent, and occasionally an even greater proportion, of the stand on much of the land where it is found, with an average of about 20 per cent. The trees reach diameters of from 12 to 15 feet and heights up to 200 feet. Average mature trees are between 4 and 6 feet in diameter and contain from 10 to 15 thousand feet of lumber.

The total stand of Sitka spruce in Washington and Oregon is nearly 11 billion board feet,[1] of which 6,100 million feet is in the four Washington counties named above, 4,375 million feet in Oregon, and 475 million feet in other counties of western Washington. Except for about 600 million feet on the Queniult Indian Reservation, 950 million feet on the Olympic National Forest, and 700 million feet of State timber, all of which is in Washington, and 300 million feet on the Siuslaw National Forest, in Oregon, the spruce is privately owned, most of it by large timber and logging companies.

Almost all of the Government timber is at present inaccessible. One-third of the privately owned timber is scattered, inaccessible, or too low a grade to be important as a source of airplane material; 2½ billion feet is in large bodies which can be reached only by extensive road and railroad construction, and about 4 billion feet is fairly accessible to existing plants. The greater part of the spruce forests is in the more easily logged portions of the region, on the lowlands or in the lower foothills.

There is estimated to be from 15 to 18 billion feet of Sitka spruce in Alaska, practically all on National Forests, but only about 1 billion feet of this is good enough in quality to yield airplane lumber. There is also estimated to be about 29 billion feet in British Columbia, probably not of the highest quality.

PRODUCTION OF LUMBER.

The average annual cut of Sitka spruce lumber from 1913 to 1917 was 288 million board feet, of which three-fourths was cut in Washington. In 1917, 14 mills reported cuts of more than 10 million feet of spruce each, while about 30 mills cut from 1 to 10 million feet each. Small mills play a very unimportant part in the production of Sitka spruce.

Under normal conditions spruce is logged with other species as it comes in the stand. With the urgent demand for spruce during the war, however, the principle of selective logging was developed very generally, and special effort was made to get more spruce, and particularly higher-grade spruce, than would normally have been obtained. Because of the large size of the timber and the heavy stands, steam logging is in general practice, although in the selective logging animals were used to some extent. Motor trucks were used in addition to the logging railroads and water transportation in bringing logs to the mills. Logging operations in the spruce region are carried on throughout the year. In this region much of the timber is cut by logging companies that do not operate sawmills, but sell their logs to sawmills.

[1] It is estimated that about 1,600 million board feet of the most accessible Sitka spruce has been cut since this estimate was made.

Most mills saw logs of all species; a few specialize on spruce. Mills in the spruce region have a capacity considerably in excess of their normal total cut of all species. Until the demand for straight-grained material for airplanes developed during the past few years, no special effort had been made to saw that kind of lumber. The urgent demand for airplane material during the war led to improved methods of sawing, which made it possible to get the maximum amount of straight-grained lumber out of the logs.

Of the 7 billion feet which will yield airplane lumber, it is estimated that 20 per cent will grade No. 1 logs, 40 per cent No. 2, and 40 per cent No. 3. No. 1 and No. 2 logs should cut from 15 to 18 per cent of wing beam stock, and it is estimated that on the average the available mature spruce will yield between 10 and 15 per cent of wing-beam material. Of the total stand of Sitka spruce, probably between 7 and 10 per cent will be suitable for wing beams.

MARKETS AND USES FOR THE LUMBER.

Sitka spruce is used for about the same purposes as the other spruces. Forty per cent of the cut of spruce lumber of the United States is normally used for construction and other purposes without further manufacture. Sixty per cent is manufactured into a large variety of products. Planing mill products consume 26 per cent. The box and crate industry, which uses mostly the lower grades of lumber, takes 25 per cent, Musical instruments, which require the best material, especially for piano sounding boards, use 2.2 per cent. Woodenware employs 2.1 per cent, and many other industries use smaller quantities.

Much of the high-grade Sitka spruce lumber is normally shipped east to the Central States, and construction material of this species has very recently begun to enter Atlantic coast markets in competition with eastern spruce. Shipments to foreign countries and to California markets usually go by water. Eastern shipments have gone by rail, but under normal conditions Atlantic coast shipments will probably take the water route.

EASTERN SPRUCE.

RED SPRUCE (*Picea rubens*). WHITE SPRUCE (*Picea canadensis*).

Picea canadensis is also known as cat spruce, bog spruce, and skunk spruce.

DISTRIBUTION.

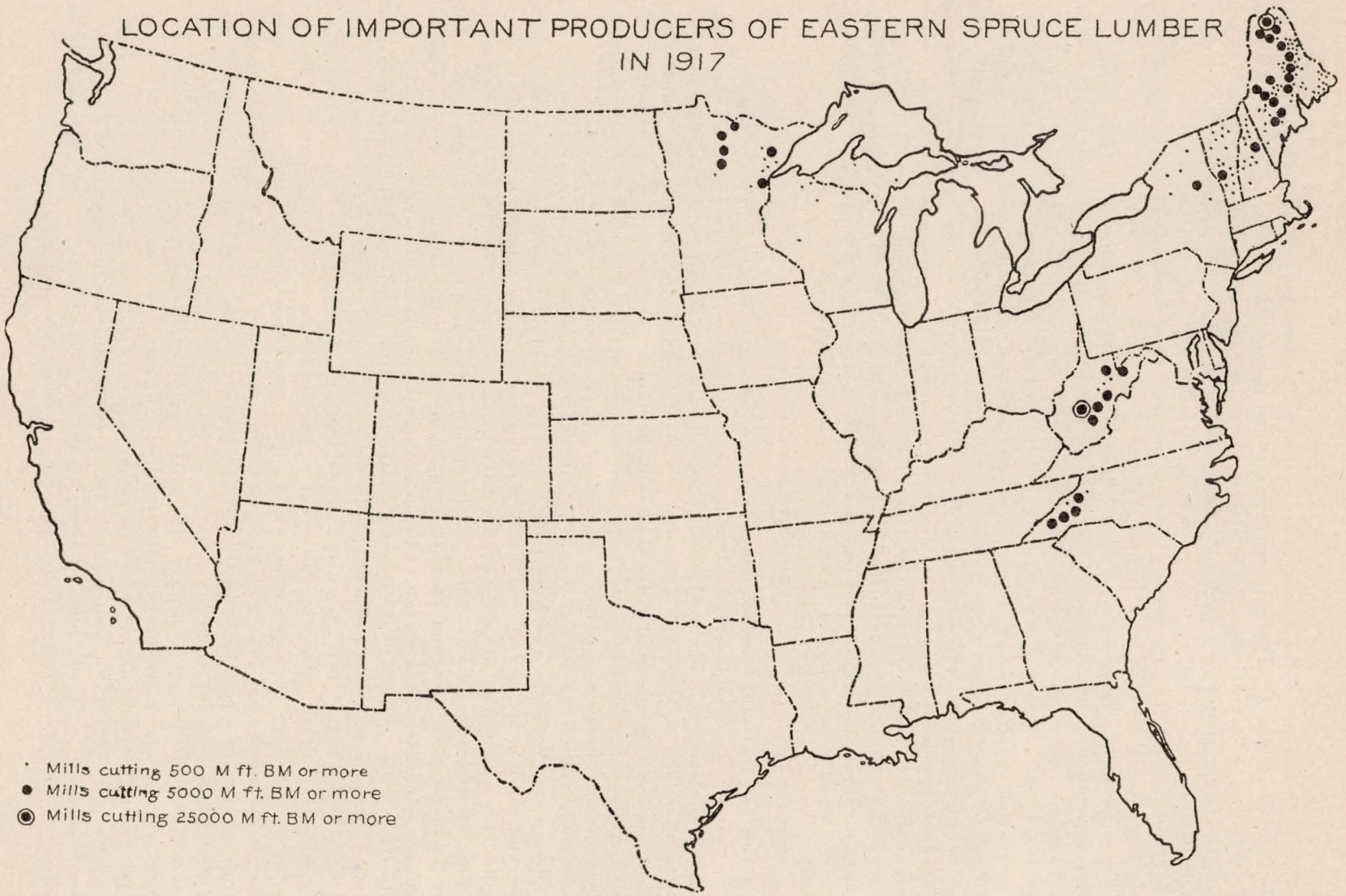
Red spruce occurs from Prince Edward's Island, along the St. Lawrence Valley to central New York and Massachusetts, and along the mountains as far south as South Carolina. White spruce is found in northern New England, the Lake States, the Black Hills of South Dakota, and Montana, and extends far to the north in Canada and Alaska. In the United States, red spruce is commercially important in northern Maine, New Hampshire, and Vermont, and in the southern Appalachians from West Virginia southward. White spruce is important chiefly in the northern part of the Lake States.

USE IN AIRCRAFT.

Red and white spruce, with Sitka spruce, are the ideal woods for the structural parts of aircraft, because in them lightness and ease of working are combined with great strength, stiffness, and freedom from hidden defects. The three species do not greatly differ in strength properties, but Sitka spruce reaches much larger sizes and, therefore, produces a larger proportion of clear lumber suitable for aircraft. Spruce is used for wing beams, ribs, struts, longerons, plywood, and, indeed, for almost every wooden part of aircraft. Even though its place may be taken to some extent by other woods as the supply of virgin spruce dwindles, it will undoubtedly continue to be a very important aircraft material so long as wood is used for these purposes.

SUPPLY OF TIMBER.

Spruce occurs at medium or high elevations, and in the northern part of its range it occupies lowlands also. In many places it forms extensive, pure or nearly pure, dense stands, especially in the more mountainous parts of its range. In other places it is found in mixed


LOCATION OF IMPORTANT PRODUCERS OF EASTERN SPRUCE LUMBER
IN 1917
Mills cutting 500 M ft. BM or more
Mills cutting 5000 M ft. BM or more
Mills cutting 25000 M ft. BM or more

MAP No. 2

stands, with northern hardwoods (birch, maple, beech, and ash), as well as balsam, hemlock, tamarack, arbor vitæ, or even white and Norway pines. Over large areas, spruce makes up from half to three-fourths of the total stand. In the southern Appalachians spruce is confined to the higher mountains. The southern Appalachian section was not opened up until a comparatively recent date, but the spruce stands there are now being tapped by railroads and most of the better-grade spruce will soon be accessible to mills. The spruce in the Northeast must be transported to the mills principally on drivable streams. Although the topography of the region is such that the greater part of the lumber is accessible to such streams, still certain large areas are somewhat out of the way.

The northeastern spruce does not reach large size. While diameters of from 2 to 3 feet are not uncommon, a great many of the trees in mature stands have diameters between 12 and 18 inches. The southern spruce averages considerably larger than that of the North. It is doubtful whether the Lake States spruce will be used to a large degree for airplane lumber. The proportion of clear material produced is not large, and much of it is in short lengths.

The total stand of spruce saw timber in the eastern United States, excluding the Lake States, is approximately 14½ billion board feet. This estimate does not include trees less than 10 inches in diameter, and in some States does not include those less than 12 inches. Maine has approximately 7½ billion feet, New Hampshire 2 billion, Vermont 200 million, New York between 3½ and 4 billion, North Carolina and Tennessee 950 million, West Virginia and Virginia 390 million. Practically all of the old-growth spruce, as well as a large part of the second growth, is owned in large units by land, lumber, or pulp companies.

PRODUCTION OF LUMBER.

During the years 1913 to 1917, the average annual cut of spruce lumber in the Northeast and the southern Appalachians was a little less than 725 million board feet, of which 360 million was sawed in Maine, 65 million in Vermont, 70 million in New Hampshire, 25 million in Massachusetts, 45 million in New York, 105 million in West Virginia, and 50 million in North Carolina. While there is considerable fluctuation in the lumber cut from year to year, due partly to labor and weather conditions and partly to variation in the demand for spruce pulpwood, the general trend indicates a reduction in the cut of spruce lumber.

For the year 1917, 14 mills in Maine, 5 in West Virginia, 4 in North Carolina, and 1 each in New Hampshire, Vermont, and New York reported cuts of between 5 and 25 million feet of spruce, and 1 mill in Maine and 1 in West Virginia reported more than 25 million feet. About 90 mills, most of them in Maine, New Hampshire, and Vermont, cut between 500 thousand and 5 million board feet. While most of the spruce mills cut lumber of other species, spruce forms the major part of the cut of most of the larger mills. Existing mills, if they were run to capacity, could saw from three to five times as much spruce as they now cut.

In the Northeast, most of the logging is done in winter. Logs are hauled out to drivable streams by animals or steam log haulers. In the South operations are carried on throughout the year. In this region, both steam and animal logging is carried on, and logs are transported to the mills by railroad. Most operators cut spruce both for lumber and for pulp. Many of them saw only the best logs into lumber and let the small and inferior material go into pulp. During the past few years nearly all of the mill operators that cut any considerable quantity of spruce lumber have become familiar with the character of material required for aircraft and with the best methods of sawing it.

It is estimated that about 3.4 per cent of the spruce in Maine (12 inches in diameter and upward) will be suitable for airplane construction. Slightly more than 5 per cent of the New Hampshire and Vermont spruce, a little less than 5 per cent of that in New York, and from 8 to 8.2 per cent of that in the southern mountains will be suitable for airplanes. These figures do not in all cases represent what is being produced at the present time, because in some instances mills are now cutting material from the choicest parts of their tracts.

MARKETS AND USES FOR THE LUMBER.

Spruce lumber is used in large quantities for general construction purposes and by industries manufacturing wooden products. As is stated in the chapter on Sitka spruce, these industries use 60 per cent of the spruce lumber cut in the United States. High-grade spruce lumber is in great demand for piano sounding boards, for clapboards, and similar uses, and in shorter lengths for butter tubs. Eastern spruce is marketed mostly in the North and East and, consequently, does not have to carry heavy transportation charges. On account of the higher value of spruce stumpage in the East, together with such other factors as the larger percentage of upper grades sawed from Sitka spruce, the spruce from the Northwest is now competing with the native lumber even on the New England market.

Some 10 to 15 million feet of eastern spruce lumber is exported in normal times, chiefly to the countries of western Europe.

DOUGLAS FIR.

(*Pseudotsuga taxifolia.*)

This species is also known as red fir, yellow fir, Oregon pine, red pine, and Douglas spruce.

DISTRIBUTION.

Douglas fir occurs through most of the forests from the Rocky Mountains to the Pacific coast, and from Mexico to central British Columbia. Only the stands west of the Cascade Range, from northern California to British Columbia, contain any considerable proportion of material suitable for aircraft construction, and, therefore, only the fir from this region is covered in the following discussion.

USE IN AIRCRAFT.

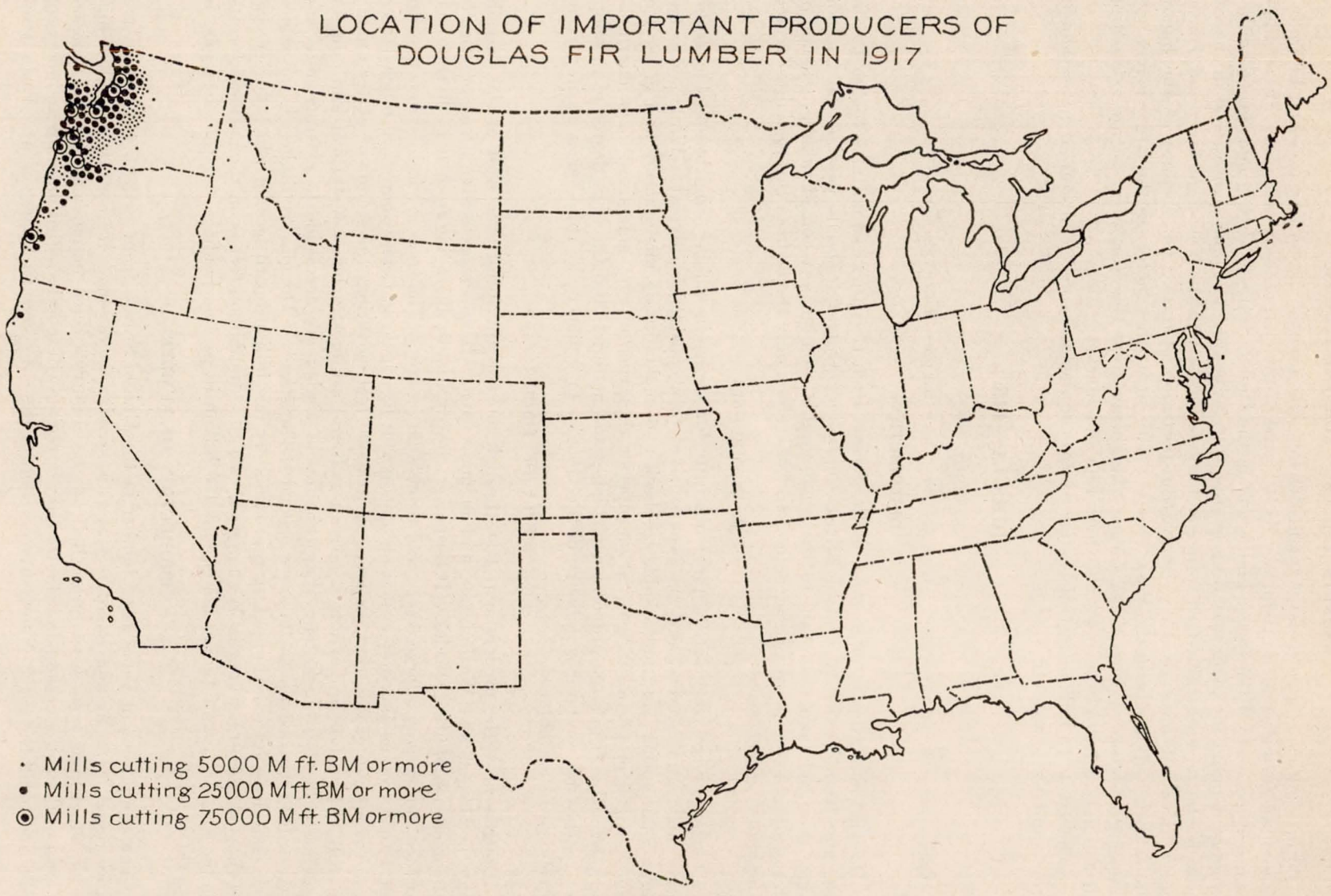
Douglas fir is a very satisfactory substitute for spruce in making wing beams, longerons, struts, and engine bearers, and has been so used to a considerable extent. While somewhat heavier than spruce, and more liable to check and shake during manufacture and in service, in its strength properties it is equal or superior to spruce of the same sizes. The enormous supply available, the large proportion of high-grade material, and the high degree of development reached by the lumber industry in the Douglas fir region make this species an important source of airplane material.

SUPPLY OF TIMBER.

Douglas fir is the predominant tree through most of the forest area west of the Cascade Range in Oregon and Washington, and in many places it covers extensive areas practically to the exclusion of other species. It forms very heavy stands, averaging from 30 to 60 thousand board feet per acre over large tracts, and reaches large sizes. The trees in virgin stands average from 3 to 6 feet in diameter and from 150 to 200 feet in height, and many are much larger. While the species grows from sea-level up to 6,000 feet elevation, the stands of better quality that will yield a fair proportion of aircraft material are mostly below 3,000 feet and offer no obstacles to logging operations. Large bodies of timber are accessible to existing mills and others will be opened up as they are needed. The stand of Douglas fir timber in the region under consideration is estimated at approximately 600 billion board feet, of which 60 per cent is in Oregon and 40 per cent in Washington. Of this, 100 billion feet is on the national forests, 30 billion on State and Indian lands, and 470 billion in private holdings, for the most part in large tracts.

PRODUCTION OF LUMBER.

The annual cut of Douglas fir lumber in the United States, from 1913 to 1917, inclusive, has averaged 5,150 million board feet, and is steadily increasing. The southern yellow pine forests, which now furnish the great bulk of the country's construction material, have passed the crest of their production, and the Douglas fir region will soon be called upon for an increasing production to fill the gap. Ninety-five per cent of the cut comes from Oregon and Washington,


LOCATION OF IMPORTANT PRODUCERS OF
DOUGLAS FIR LUMBER IN 1917
· Mills cutting 5000 M ft. BM or more
• Mills cutting 25000 M ft. BM or more
◉ Mills cutting 75000 M ft. BM or more

MAP No. 3

and more than 80 per cent of this, or approximately 4 billion feet, from west of the Cascades. All but a comparatively insignificant part of this is produced by large, well-equipped, up-to-date mills, of which there are about 180. Their rated capacity on a one-shift basis is between 9 and 10 billion board feet a year or, allowing for other species cut along with the fir, about double their present output.

Because of the large sizes of the timber, steam logging and railroad hauls are the rule. Logs are ordinarily cut from 32 to 40 feet long. Stands are generally cut clear of all merchantable material, taking all species as they come. Operations are continued throughout the year. Many logging companies have no mill connections but sell their logs to sawmills.

Under normal conditions no particular effort is made to saw out straight-grained lumber. The demand for such material during the past two years led to the development of methods for producing it, and these will no doubt be continued and improved upon if the demand continues.

Under present standards most of the airplane material will come from the grades No. 2 clear and better. The percentage of the cut in these grades varies with different stands, but for the region averages about 20 per cent. It is estimated that half of this lumber will not be suitable for aircraft, on account of low density, pitch pockets, and a little spiral grain. The other half, or 10 per cent of the total cut of 4 billion feet, should be suitable for aircraft, and probably 60 per cent of that, or 6 per cent of the total cut, will meet present standards for wing beams.

MARKETS AND USES FOR THE LUMBER.

Of the total cut of Douglas fir lumber, approximately 45 per cent, including most of the better-grade material, is further manufactured. The greater part, 40 per cent of the cut, goes into flooring, interior finish, sash and doors, and other planing mill products. Between 15 and 20 per cent of all wood used for these purposes in the United States is Douglas fir. Of the total cut, 1.8 per cent goes into tanks and silos, 1.7 per cent into cars, and 0.9 per cent into ships and boats. Considerable quantities are used for pumps and pipe, furniture, boxes and crates, fixtures, paving, rollers, agricultural implements, and woodenware.

Douglas fir is being sold in increasing quantities in the eastern United States. It has for a number of years been exported in considerable quantities to South America, China, and Australia, and to a very limited extent to European countries.

PORT ORFORD CEDAR.

(*Chamaecyparis lawsoniana.*)

This species is also known as Lawson cypress, Oregon cedar, and white cedar.

DISTRIBUTION.

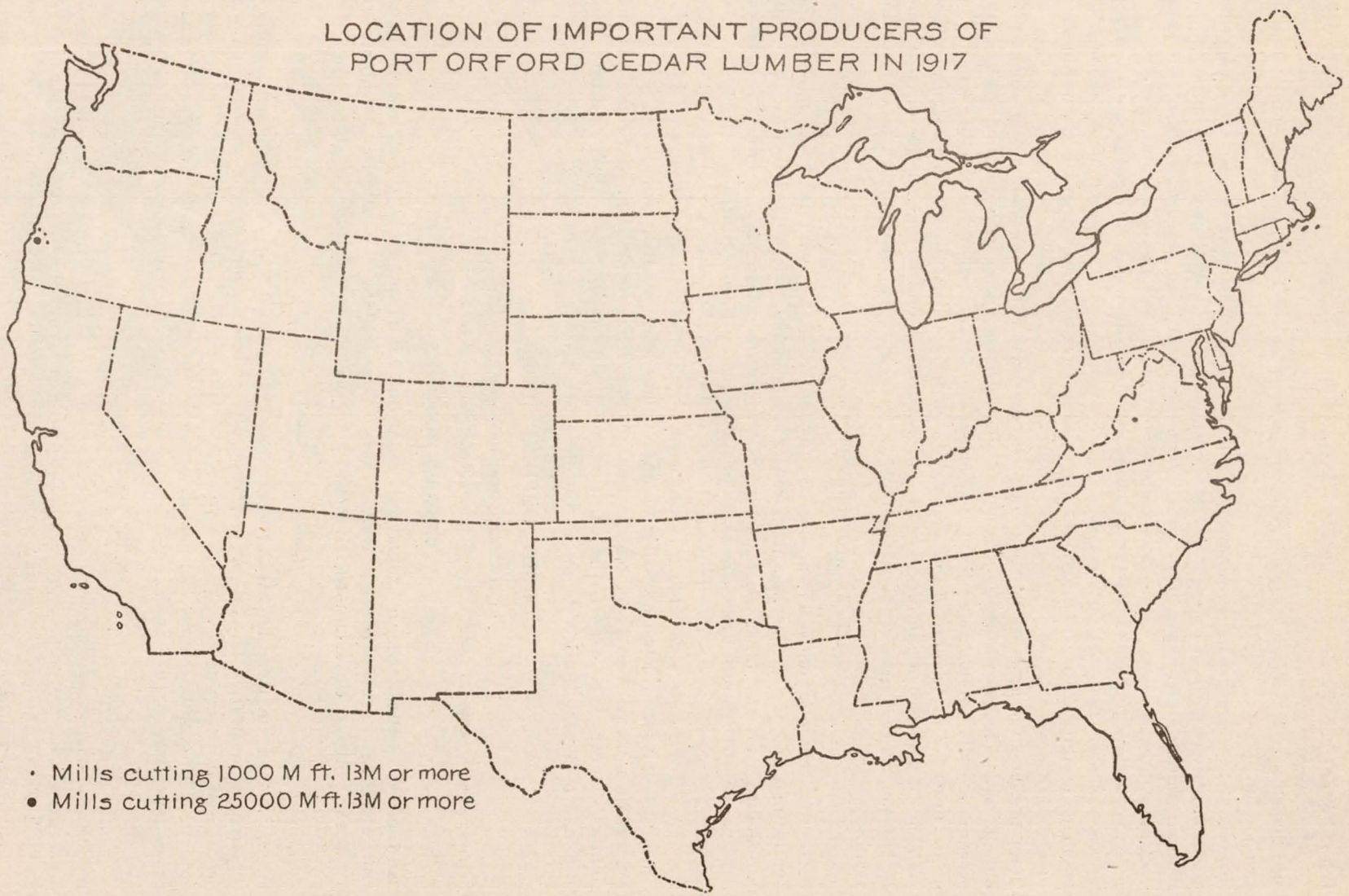
Stands of Port Orford cedar of commercial importance are confined to a strip from 20 to 25 miles wide along the Pacific coast in Coos and Curry Counties, Oreg. Scattered individuals are reported as far south as the Klamath River and Mt. Shasta, in California.

USE IN AIRCRAFT.

While somewhat heavier than Sitka spruce, Port Orford cedar is equal or superior to spruce in all its strength properties, and has been successfully used as a substitute for spruce in making wing beams and for other uses to which spruce is adapted. While this species is satisfactory for aircraft use, the limited supply and small annual output indicate that it will probably not play a very important part in the future development of the airplane industry.

SUPPLY OF TIMBER.

Port Orford cedar does not grow in pure stands, but is scattered through forests of Douglas fir, hemlock, grand fir, and western red cedar. It usually comprises from 25 to 30 per cent of the stand. Trees of this species reach very large size. Practically all of the standing Port Orford cedar is virgin timber, and fairly accessible to existing mills. The stand is estimated


LOCATION OF IMPORTANT PRODUCERS OF
PORT ORFORD CEDAR LUMBER IN 1917
· Mills cutting 1000 M ft. 13M or more
• Mills cutting 25000 M ft. 13M or more

MAP No. 4

at about 750 million feet, of which 250 million feet is on the Siskiyou National Forest, and the remaining 500 million feet, about equally divided between Coos and Curry Counties, is privately owned. Most of this is in the hands of a small number of large firms.

PRODUCTION OF LUMBER.

The total cut of Port Orford cedar in 1917 was about 35 million board feet, which is probably about the average annual production. The bulk of it is cut by one firm and only four mills cut more than one million feet each. Cedar is ordinarily cut as it comes in the stand, and makes up about 28 per cent of the total cut of the mills which produce it. Existing plants, if run to full capacity on a one-shift basis, could cut approximately 25 per cent more than they did in 1917.

Logging is by steam, and log lengths of from 32 to 40 feet are commonly cut. During the drive for wing-beam material for the war, sawing methods adapted to the maximum production of straight-grained material were used; but, since straightness of grain is not one of the main considerations in cutting lumber for most commercial uses, it is possible that no special effort will be made to produce that kind of material in the future.

About 20 per cent of the cut falls in the clear grades (No. 1 and No. 2), and it is estimated that 60 per cent of this or 12 per cent of the total cut, is of airplane grade. The other 40 per cent will be disqualified on account of low density, spiral grain, or other defects.

MARKETS AND USES FOR THE LUMBER.

The upper grades of Port Orford cedar are used for interior finish, caskets, and boat building. The lower grades go into general construction. Much of the output is normally used on the Pacific coast, and some is exported to Japan.

FIR.

GRAND FIR (*Abies grandis*).

This species is also known as lowland white fir, white fir, Oregon white fir, and silver fir.

SILVER FIR (*Abies amabilis*).

This species is also known as lovely fir, amabilis fir, red fir, red silver fir, and larch.

NOBLE FIR (*Abies nobilis*).

This species is also known as larch, and red fir.

WHITE FIR (*Abies concolor*).

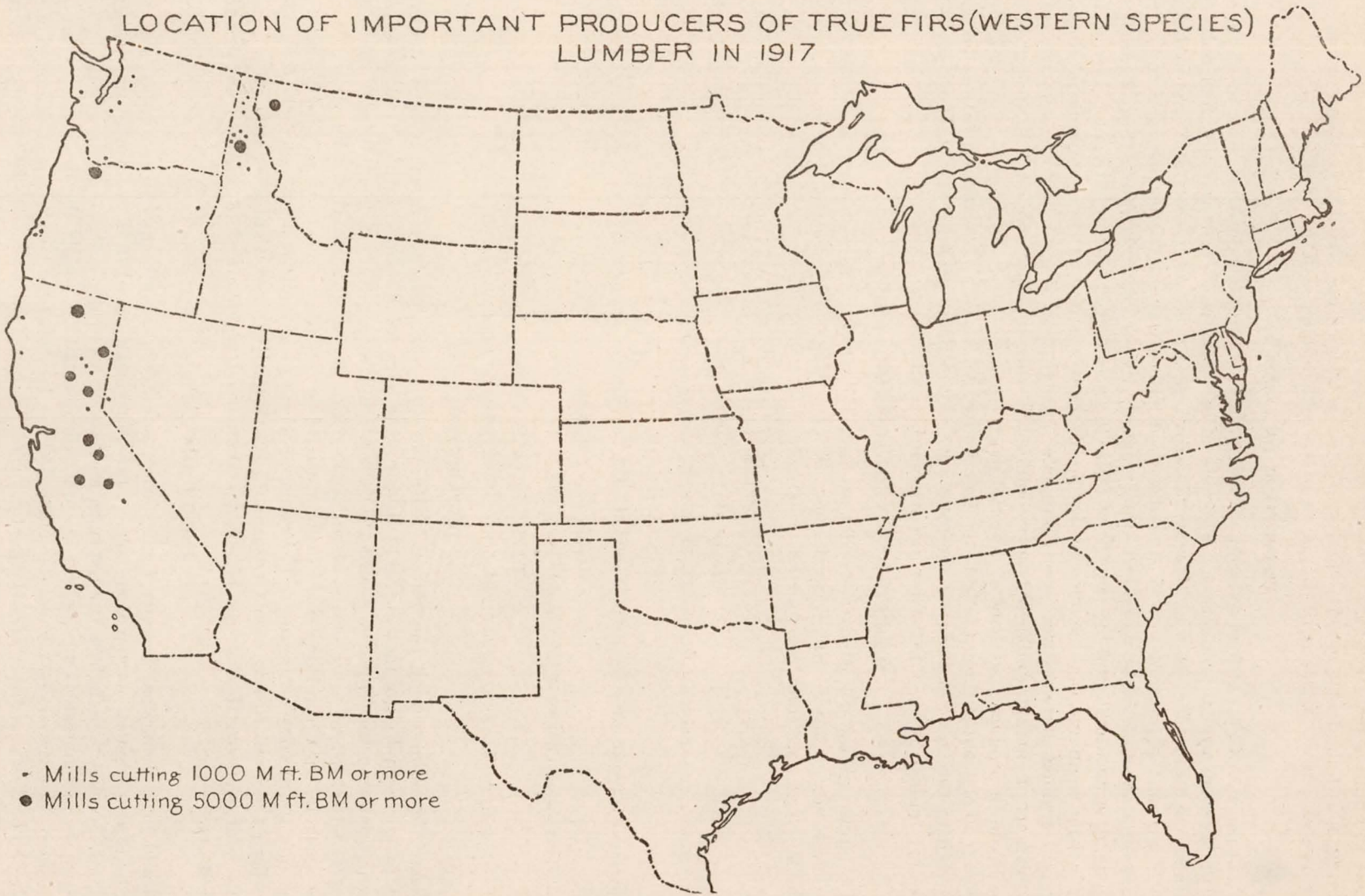
This species is also known as California white fir, Colorado white fir, balsam, and silver fir.

DISTRIBUTION.

Grand fir occurs along the Pacific coast and along the Cascade range from Vancouver Island to northern California, and extends into northern Idaho and northwestern Montana. Silver fir occurs on the upper slopes of the Cascade and Coast Ranges from British Columbia to central Oregon, and is most abundant in the Olympic Mountains of Washington. Noble fir also occurs on the Coast Ranges of Washington and Oregon, and along the Cascades of northern Oregon and southern Washington. The range of white fir extends from the Rocky Mountains of southern Colorado to northern Oregon, and southward through California to New Mexico, Arizona, and northern Mexico. It is of large commercial importance only in the Sierra region of California.

USE IN AIRCRAFT.

Grand fir is somewhat heavier than spruce, but in strength compares favorably with it. Silver fir is also slightly heavier than spruce, but practically equal to it in most of its strength properties. Noble fir is lighter than spruce, and about as strong. White fir is a little lighter than spruce, and almost as strong, except in shock resistance. While the firs have not so far been used to any extent in airplane construction, at least the first three species named may prove to be fairly satisfactory substitutes for spruce in making wing beams and struts. As far as present information shows, the other firs are not strong enough for such use. Because of their light weight, however, the firs are suitable for core work in producing plywood.


LOCATION OF IMPORTANT PRODUCERS OF TRUE FIRS (WESTERN SPECIES) LUMBER IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 5000 M ft. BM or more

MAP No. 5

SUPPLY OF TIMBER.

The firs usually occur in mixed coniferous forests, although in some situations they form practically pure stands over considerable areas. Associated species in the northwest coast region are Douglas fir, western hemlock, western red cedar, Sitka spruce. In the Montana-Idaho region the stands include western white pine, Douglas fir, western red cedar, western larch, western yellow pine, western hemlock. The white fir in the Sierra region is associated with western yellow, Jeffrey, and sugar pines, Douglas fir, red fir, incense cedar, and occasionally with the bigtree. Grand fir occurs chiefly at low and medium elevations, and there it can conveniently be logged along with Douglas fir and its other associates. Silver fir is a tree of the higher slopes, and very little of it can be considered accessible under present conditions. The same is true, but to a somewhat less extent, of noble fir. White fir grows in rough mountain country, and much of it is hard to get at. It is commonly taken when found on tracts that are being cut over primarily for other species.

The total stand of grand fir is estimated at about 13½ billion board feet, of which nearly 5 billion feet is in Washington, 4 billion feet in Oregon, and 4½ billion feet in Idaho and Montana. Two-thirds of it is owned by the Government, principally on National Forests; the rest is owned by lumber and timber companies. It is estimated that there is 35 billion feet of silver fir, and that 32 billion feet of it is in Washington, owned about half-and-half by the Government and by private companies. Of the 4 billion feet of noble fir, two-thirds is owned by the Government and one-third by private concerns. Three billion feet of it is in Oregon. There is about 35 billion feet of white fir in California, 5 billion feet in Oregon, and possibly 1½ billion feet scattered in other States. About half of it is on the National Forests and the other half is in the hands of large private owners.

PRODUCTION OF LUMBER.

The average annual cut of all species classed as "white fir," which includes the four species under discussion, as well as red fir (*Abies magnifica* and *A. shastensis*) and alpine fir (*A. lasiocarpa*), was about 110 million feet a year up to 1916. Of this it is estimated that approximately 45 million feet each were white fir and grand fir, and between 5 and 10 million feet each noble fir and silver fir. With rising prices, which made it possible to log more of the fir, the cut rose in 1916 to about 190 million feet, and slightly exceeded that amount in 1917. The cut of grand fir is estimated to be now about 64 million feet, of which 53 million comes from northern Idaho and adjacent parts of Montana and Washington; that of silver fir is judged to be about 8 million feet, all in Washington; that of noble fir, 6 million feet, cut by one firm; and that of white fir, approximately 100 million feet, of which 87 million feet is cut in California and 11 million feet in Oregon.

The greater part of this lumber, probably at least 90 per cent of it, is produced by large mills, which cut fir only incidentally as it comes in the run of logs. Thirty mills report cuts for 1917 of between 1 and 5 million feet of fir, and 11 report cuts in excess of 5 million feet.

Steam logging is very general in the fir region, and nearly all operators use logging railroads. In the northwest coast region logs are cut long, while in the northern Idaho region and in the Sierras 16-foot lengths are the rule.

Since, with the exception of the noble fir, the logs make only relatively low-grade material, little care is used at most mills in sawing them up. The percentage of clear material that can be obtained varies rather widely in different localities. The best available estimates indicate that about 1 per cent of the white fir and grand fir, from 1 to 2 per cent of the silver fir, and 10 per cent of the noble fir will be suitable for airplane construction.

MARKETS AND USES FOR THE LUMBER.

The great bulk of the fir lumber produced is used in construction work without further manufacture. The best material is made into flooring, sash, doors, interior finish, and shelving. The box and crate industry uses a small percentage of the output. While some fir lumber may reach eastern markets along with shipments of Douglas fir and western pine, by far the greater part of it is used in the West.

WHITE PINE.

(*Pinus strobus.*)

This species is also known as Weymouth pine, northern pine, spruce pine, and soft pine.

DISTRIBUTION.

White pine occurs from Newfoundland to Lake Winnipeg, and southward through the Lake States, the New England States, and in the Appalachians as far south as northern Georgia.

USE IN AIRCRAFT.

Although somewhat softer, less shock-resistant, and less stiff than spruce, white pine is comparatively strong and light, uniform in structure, easy to dry and work, and stays in place well. It is a fairly satisfactory substitute for spruce in making wing beams and for other uses, and has been so employed. Because of its lightness, it makes excellent cores for plywood. Norway (or red) pine (*Pinus resinosa*), which is cut and marketed along with white pine in the northern part of its range, may also be used as a spruce substitute.

The remaining supply of virgin white pine is fast disappearing; and, since very little wing beam material can be obtained from second-growth, this species will not long continue to be an important airplane wood, except possibly for plywood.

SUPPLY OF TIMBER.

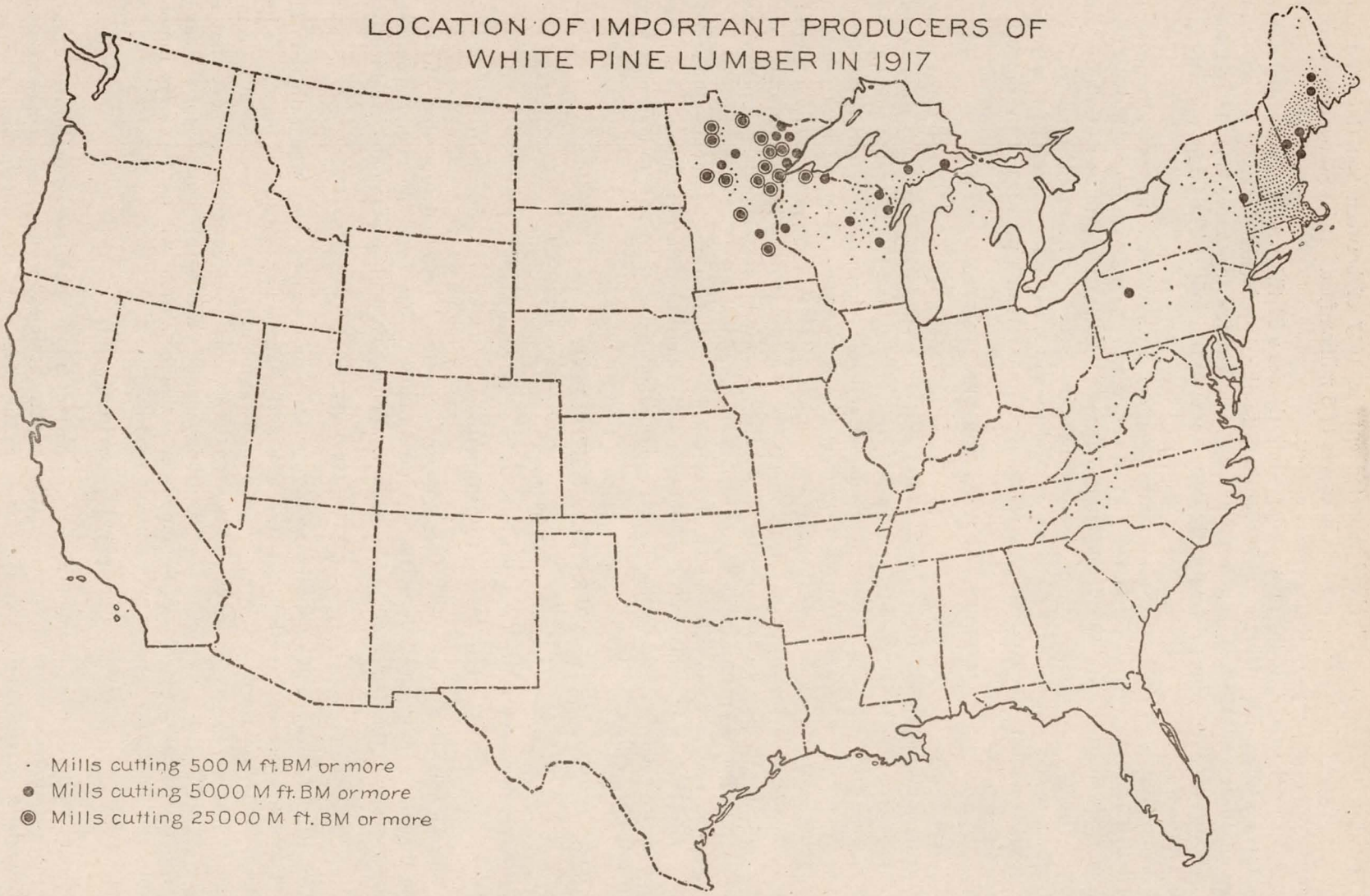
Pure stands of white pine or mixed stands of white and Norway pine still cover extensive areas in Minnesota. Other areas are covered with mixed stands of pine, hardwoods, and hemlock, in which pine may or may not be the predominant species. There are practically no virgin pine stands left in the Northeast. Most of the pine in this region is now in small tracts, many of which are pure pine, while others contain pine in various mixtures. While these stands are frequently heavy, they contain very little clear material suitable for wing beams and similar uses. The virgin white pine in the Appalachian region is now chiefly in the South, from West Virginia southward. In this region it occurs scattered through mixed hardwood and hemlock stands, and its average quality is not so high as is that of the pine in the Lake States. Virgin white pine averages 3 feet and more in diameter and 100 feet or more in height.

Only the supply of virgin timber need be considered in discussing wood suitable for aircraft construction. This is roughly estimated at 12 billion board feet, of which 10 billion feet (25 per cent of it Norway pine) is in the Lake States (chiefly in northern Minnesota), and 2 billion feet in the southern Appalachians. It is practically all on large tracts owned by land and lumber companies, and most of it is accessible and available for existing mills.

PRODUCTION OF LUMBER.

From 1913 to 1917, the average annual cut of white pine lumber was nearly 2,100 million feet, as against an average of about 3,500 million feet during 1907 to 1912. The white pine cut has been steadily falling off for a number of years as the supplies of virgin timber have become more nearly exhausted. It may be expected to continue to fall rapidly until the few billion feet left in Minnesota are cut, after which a fairly constant amount will be cut each year from second-growth stands.

Of the present cut, a little more than half, or about 1,200 million feet, comes from virgin timber. About 900 million feet of this is cut in Minnesota, 210 million feet in Wisconsin and Michigan, and 75 million feet in the southern Appalachians. Small amounts of virgin white pine are cut in Maine, Pennsylvania, and New York. Ninety per cent of the virgin pine is sawed by large mills, a number of which cut 25 million feet or more a year. Fourteen mills in Minnesota and one in Wisconsin reported cuts of this size in 1917. These mills cut white and Norway pines principally; some of them cut little of any other species. In the South, white pine usually forms only a minor part of the cut of the mills that produce it. The second-growth pine of the Northeast is almost entirely cut by small stationary or portable mills.


LOCATION OF IMPORTANT PRODUCERS OF
WHITE PINE LUMBER IN 1917
Mills cutting 500 M ft. BM or more
Mills cutting 5000 M ft. BM or more
Mills cutting 25000 M ft. BM or more

MAP No. 6

Some 350 operators in New England reported cuts in 1917 of between 500 thousand and 5 million feet, and only six reported cuts in excess of 5 million feet. Lake States mills have a total capacity far in excess of their present output.

Logging in the Lake States pine region is mostly done in the winter, since surface conditions favor hauling when the ground is frozen. In the Appalachians logging is carried on throughout the year. Most operators use animals, and cut few logs more than 16 feet long, except of Norway pine, which is frequently cut 18 and 20 feet long. The larger operators use logging railroads.

Straight grain is a characteristic of white pine, and little effort is necessary to produce material of that quality. It is estimated that 85 per cent of the material graded B Select and better, or from 50 to 60 per cent of that graded D Select and better, will be suitable for airplane use. In the Lake States region about 14 per cent of the cut from old stands is D and better, which would make from 7 to 8½ per cent of the cut suitable for aircraft, if it were cut in the proper sizes. In the Appalachians probably not more than 4 per cent of the cut would be satisfactory.

MARKETS AND USES FOR THE LUMBER.

White pine, once the most widely used lumber in the United States for general construction and other purposes, has come to be more and more a wood for special uses, and only a very small part of the cut is now used in its rough form. Half of the total cut goes into planing mill products—sash, doors, blinds, siding, and similar articles, which require fairly high-grade material. Nearly two-fifths is used by the box and crate industry, which, at least until the last few years, used white pine more than any other wood. This industry uses chiefly low-grade lumber. Considerable quantities of upper-grade white pine are used not only in ship and boat building, but also for patterns, tanks, silos, furniture, and musical instruments. Upper grades of Norway pine go into planing mill products, ladders, and cars.

White pine reaches a somewhat extended market; but, now that it is largely used by manufacturing industries, a great part of it is sold in the Northern and Eastern States. Facilities for shipping are good, for most of the large mills are so located as to be able to transport their output either by rail or by water.

WESTERN WHITE PINE.

(*Pinus monticola.*)

This species is also known as Idaho white pine, mountain pine, and silver pine.

DISTRIBUTION.

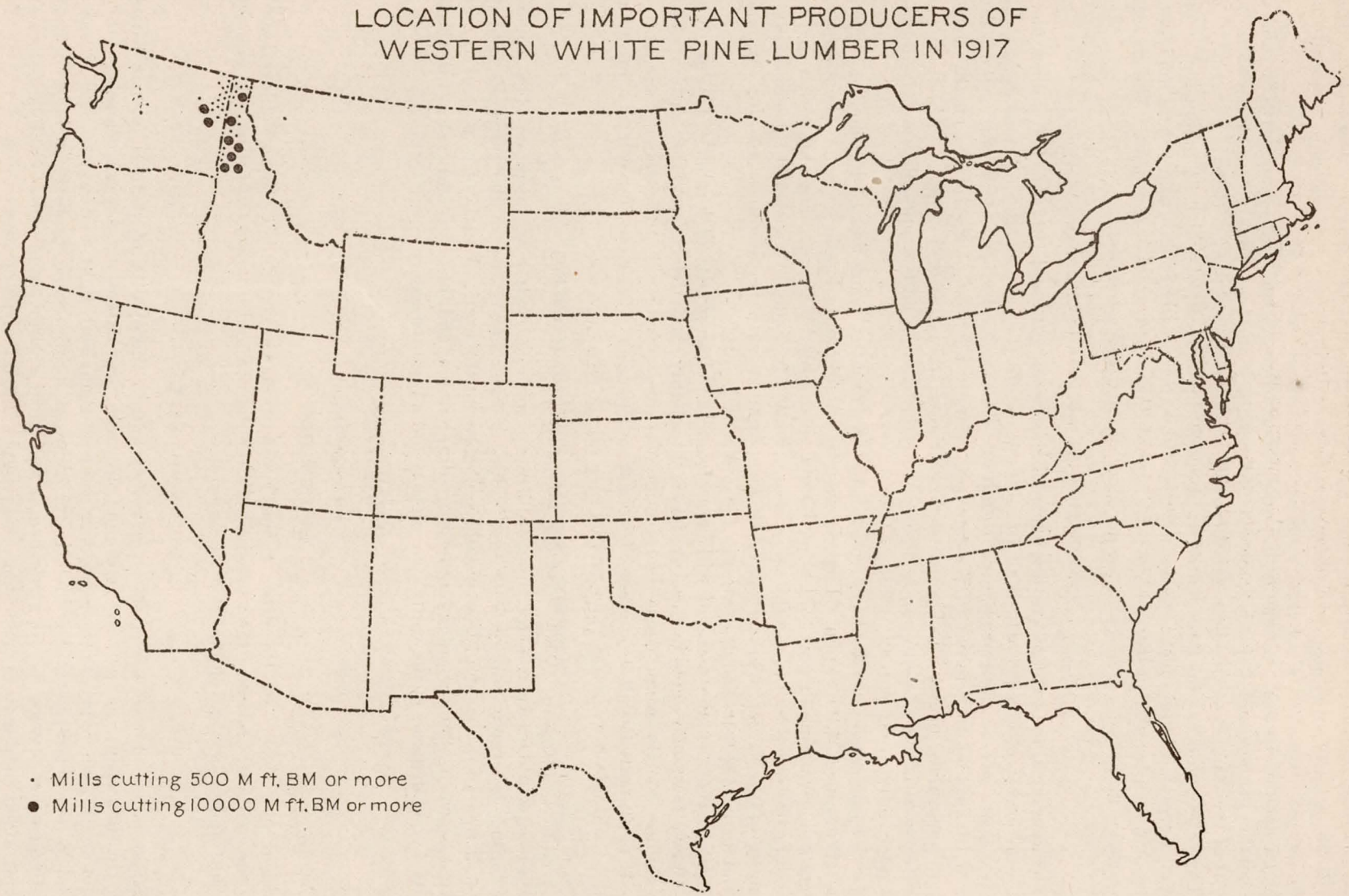
While the range of this species extends from southern British Columbia to western Montana and south along the Cascades and Sierras to central California, the region of its great commercial importance is in the Panhandle of Idaho and in adjacent parts of Montana and Washington.

USE IN AIRCRAFT.

While slightly heavier than spruce, western white pine compares very well with it in all strength properties except hardness. It makes a fairly satisfactory substitute for spruce for wing beams and similar uses. It is also a good material for plywood cores because of its comparative lightness. However, because of the relatively small percentage of the cut that is available for airplane use, and because of the abundance of other woods suitable for the same purpose, it is likely that western white pine under normal conditions will not be a very important source of material for the manufacture of aircraft.

SUPPLY OF TIMBER.

Western white pine occasionally appears in pure or almost pure stands on limited areas, but is more commonly found in mixture with western hemlock, western red cedar, western larch, Douglas fir, grand fir, and lodgepole pine. In the region of its best development it occurs at low and middle elevations, but in the coast region it is more a tree of the higher elevations,


LOCATION OF IMPORTANT PRODUCERS OF
WESTERN WHITE PINE LUMBER IN 1917
· Mills cutting 500 M ft. BM or more
● Mills cutting 10000 M ft. BM or more

MAP No. 7

where, however, it usually constitutes only a very insignificant proportion of the stand. The tree reaches a fairly large size, with diameters frequently in excess of 5 feet and heights from 100 to 150 feet at maturity. Larger sizes are not uncommon.

Logging conditions are not equally favorable everywhere in the white-pine territory, and a large portion of the stand as yet is somewhat inaccessible, but it is estimated that from 15 to 20 per cent of the stand is available to existing mills.

The total stand has been estimated at about 29 billion feet, of which 6½ billion feet is on National Forests, 3 billion feet is owned by the States (principally Idaho), and 19½ billion feet is held by private interests, mostly in large holdings of lumber companies or railroads. The greater part of this is in northern Idaho and the northeast corner of Washington.

PRODUCTION OF LUMBER.

The average annual cut of western white pine between 1913 and 1917 was 350 million feet, and the general tendency indicates a slight increase, except that abnormal conditions during the past two years have caused production to fall off. About 80 per cent of the cut is normally made in Idaho, and 15 per cent in Washington. Ninety per cent of the total is cut by large, well-equipped mills, nearly all of which saw associated species as well as pine. About 30 per cent of their total cut is white pine. The capacity of existing mills would allow nearly double the present cut.

The logging season usually lasts from six to eight months, being limited by the deep snows which fall in much of the region. Logs are usually cut 16 feet or less in length. The majority of operators use animal logging, but a few large concerns log by steam. Logs are either driven to the mills or carried by rail. While no attempt is usually made to saw straight-grained material, most of the larger operators have become familiar with the requirements for airplane material during the war, and can saw it if it is in demand.

Most of the airplane material will come from the clear grades of lumber. The grading rules allow a few small knots in these grades, and probably these defects, together with crooked grain and low density, would cause the rejection of a small proportion of the upper-grade material. It is estimated that an average of from 2 to 3 per cent of the cut of western white pine would be suitable for aircraft construction.

MARKETS AND USES FOR THE LUMBER.

Western white pine is used for about the same purposes as eastern white pine. The upper-grade lumber is largely employed for sash, doors, interior finish, and similar purposes, and is marketed to a large extent in the agricultural States to the east. A little of it goes as far as the Atlantic coast. Lower-grade lumber is used in building and for boxes and crates, for which there is a good demand in the white-pine section and adjacent regions.

SUGAR PINE.

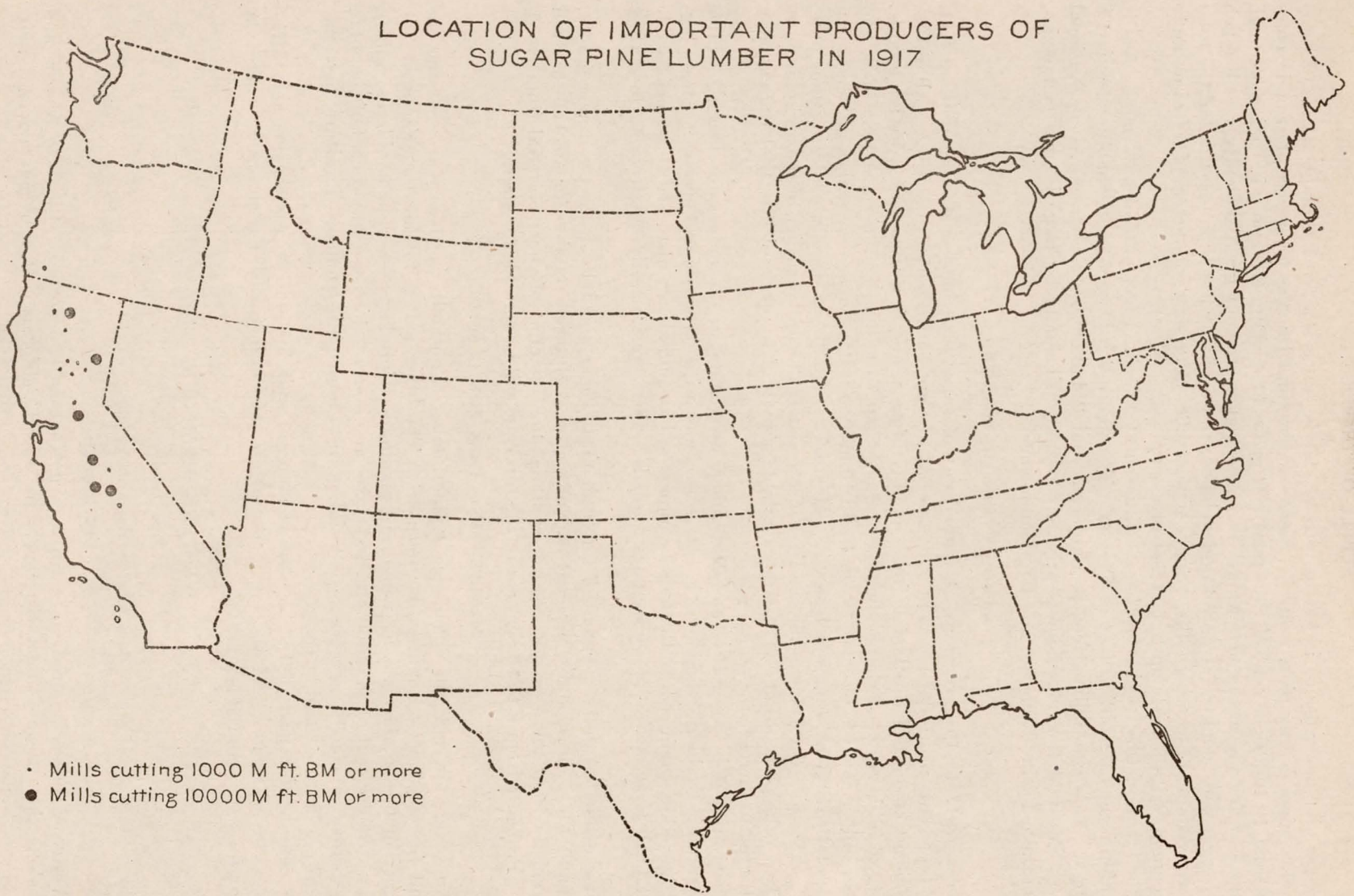
(*Pinus lambertiana.*)

DISTRIBUTION.

Sugar pine occurs on the Coast ranges of southern Oregon and northern California and along the southern Cascades, the west slopes of the Sierras, and in lower California. It is most abundant and of best development in the Sierras.

USE IN AIRCRAFT.

Sugar pine is low in shock resisting ability and in the quality of stiffness, and it varies widely in its strength properties. It is not, therefore, well adapted for wing beams or other parts of aircraft where great strength is a requisite. Being soft, light, and easy to work, it may be used in less critical parts, particularly for plywood cores. Since, however, it is likely that spruce and other species cut for wing beams will yield a large supply of suitable small-sized material, sugar pine may never become very important for airplane uses.


LOCATION OF IMPORTANT PRODUCERS OF
SUGAR PINE LUMBER IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 10000 M ft. BM or more

MAP No. 8

SUPPLY OF TIMBER.

Sugar pine never occurs in extensive pure stands, but is scattered through stands of western yellow pine, Jeffrey pine, white fir, incense cedar, and Douglas fir, where it usually comprises from 10 to 30 per cent of the stand. It grows at medium elevations in rolling or rough country and, for the most part, where it can be logged without great difficulty. Still much of the sugar pine country is as yet undeveloped, and probably less than one-third of the total stand is available to existing mills. Sugar pine reaches large sizes; diameters of 6 feet or more are common, with heights up to 200 feet or even more.

The stand of this species has been estimated at 45 billion feet, of which 33 billion feet is in California and 12 billion feet in Oregon. The figure for Oregon is probably very much too high. Fourteen billion feet in California and 2 billion feet in Oregon is on National Forests. Most of the remainder is privately owned, principally by large lumber companies, the Southern Pacific Railroad, and large landowners.

PRODUCTION OF LUMBER.

From 1913 to 1917 the average annual cut of sugar pine lumber was 140 million feet, which represents nearly 30 per cent increase over the cut between 1907 and 1912. All but an insignificant amount of this lumber was cut in California, and 90 per cent of it by large mills. In 1917, 6 mills reported the production of more than 10 million feet of sugar pine each, and 11 other mills reported cuts of between 1 and 10 million feet. Sugar pine makes up one-fourth of the total cut of the mills which saw it. Most of these mills cut chiefly western yellow pine, with some white fir, Douglas fir, and incense cedar. The mill capacity of the region is more than twice the present cut. The large available supply of timber indicates that the cut may be expected to increase for some time.

Logs are cut between May and November, deep snow in the mountains making winter logging impracticable. Sugar pine is cut as it comes with its associated species. Steam logging is generally practiced by the larger companies, but animals are also used to a considerable extent. All large operators use logging railroads. Logs are generally cut from 10 to 20 feet long.

It is estimated that 9 per cent of the total cut of sugar pine falls in the two upper grades, No. 1 and No. 2 clear, and 4 per cent in No. 3 clear. Material suitable for airplane use will come chiefly from these grades, together with a small amount of short material from No. 1 shop. Probably from 9 to 10 per cent of the total cut will be suitable for aircraft.

MARKETS AND USES FOR LUMBER.

Approximately half the cut of sugar pine lumber is normally used as it comes from the sawmill for construction and similar purposes. The other half is further manufactured into a variety of forms, chief among which are planing-mill products (sash, doors, blinds, finish), which use 26 per cent of the total cut, and boxes and crates, which use 20 per cent of the total. Small quantities, chiefly high-grade material, go into musical instruments, furniture, patterns, woodenware, fixtures, and boats.

A considerable part of the high-grade material finds its way to eastern markets The lower grades of lumber and the box material are used principally in California, where the demand for such material is great.

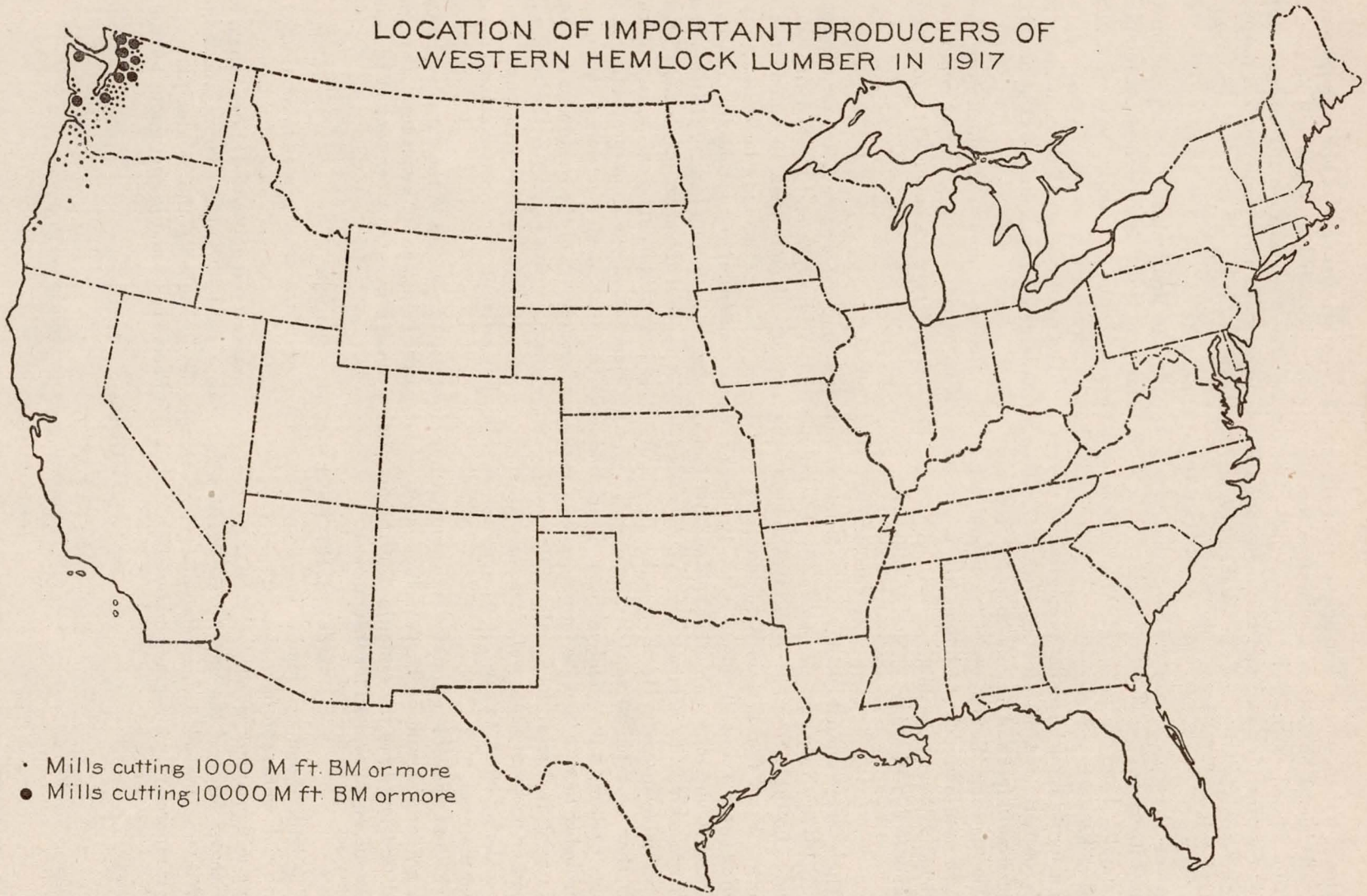
WESTERN HEMLOCK.

(*Tsuga heterophylla.*)

This species is also known as Prince Albert's fir and Alaska pine.

DISTRIBUTION.

Western hemlock occurs from northwestern Montana and northern Idaho to Alaska, and south along the Cascades and Coast ranges to central California. It is of commercial importance in the Pacific coast region from southern Oregon to Alaska.


LOCATION OF IMPORTANT PRODUCERS OF
WESTERN HEMLOCK LUMBER IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 10000 M ft. BM or more

MAP No. 9

USE IN AIRCRAFT.

Heavier than spruce, but lighter than Douglas fir, western hemlock is low in shock resistance. It might be used as a substitute for spruce, but it is probable that it will be so used only to a limited extent so long as supplies of better material are available. It makes a satisfactory core for plywood, and may sometimes be of considerable importance for this purpose, since the supply is large and the wood comparatively cheap.

SUPPLY OF TIMBER.

Along the Pacific coast, western hemlock is usually the predominant species in mixed stands with spruce, western red cedar, Douglas fir, and grand fir. It is sometimes found in pure stands along the coast of Washington and Oregon, while in Alaska extensive pure stands of hemlock or mixed stands of hemlock and Sitka spruce are common. Along the Cascades it forms a much smaller proportion of the stand. The timber is nearly all in dense virgin stands, on both lowlands and higher slopes. Trees reach large size, with diameters at maturity of from 6 to 10 feet and heights up to 200 feet.

The stand in Washington, Oregon, and Alaska is estimated at about 132 billion board feet, of which approximately 57 billion feet is privately owned, chiefly by large timber companies, and 75 billion feet by the public, mostly on National Forests. Thirty-three billion feet is in Oregon, 54 billion feet in Washington, and 45 billion feet in Alaska.

PRODUCTION OF LUMBER.

The average annual cut of western hemlock lumber averaged 325 million feet for the years 1913 to 1917. Nearly 85 per cent of it was produced in Washington and most of the rest in Oregon. In 1917, 10 mills, all in Washington, reported cuts of more than 10 million feet of hemlock. Forty-four mills in Washington, 19 in Oregon, 1 in California, and 1 in Idaho reported cuts of between 1 and 10 million feet. Hemlock is considered an inferior species by most operators, and is cut along with other species only incidentally. In selecting logging chances, areas which run heavily to hemlock are usually passed by for those with larger proportions of the more valuable species. Hemlock makes up about 11 per cent of the cut of the mills reporting it. If they operated to capacity (one shift) and cut hemlock in the same proportion as at present, existing mills could increase their production more than 50 per cent. Production will probably tend to increase for many years as the lumber industry of the Northwest develops.

Logging is carried on for about 10 months in the year. Steam logging is the rule, with railroad or, in some cases, water transportation. Logs are cut from 32 to 40 feet long. Operators make no effort to saw for straightness of grain, but attempt to get a maximum amount of clear material.

The best available estimates indicate that not more than 3 per cent of the cut is in the two upper grades of hemlock, which include most of the material suitable for airplanes. It is estimated that not more than one-third of the material in these grades, or 1 per cent of the total lumber cut, could be used for this purpose.

MARKETS AND USES FOR THE LUMBER.

The bulk of hemlock lumber (including eastern and western species) is used in the rough for construction work, and only about 30 per cent is further manufactured. Most of this goes into planing-mill products, which consume 17 per cent of the cut, and into boxes and crates, which use 8 per cent. Most of the upper-grade western hemlock is used for finish, flooring, and siding.

Western hemlock is marketed along with Douglas fir. Probably the greater part of it, being comparatively low-grade material, is used on the Pacific coast and in contiguous territory.

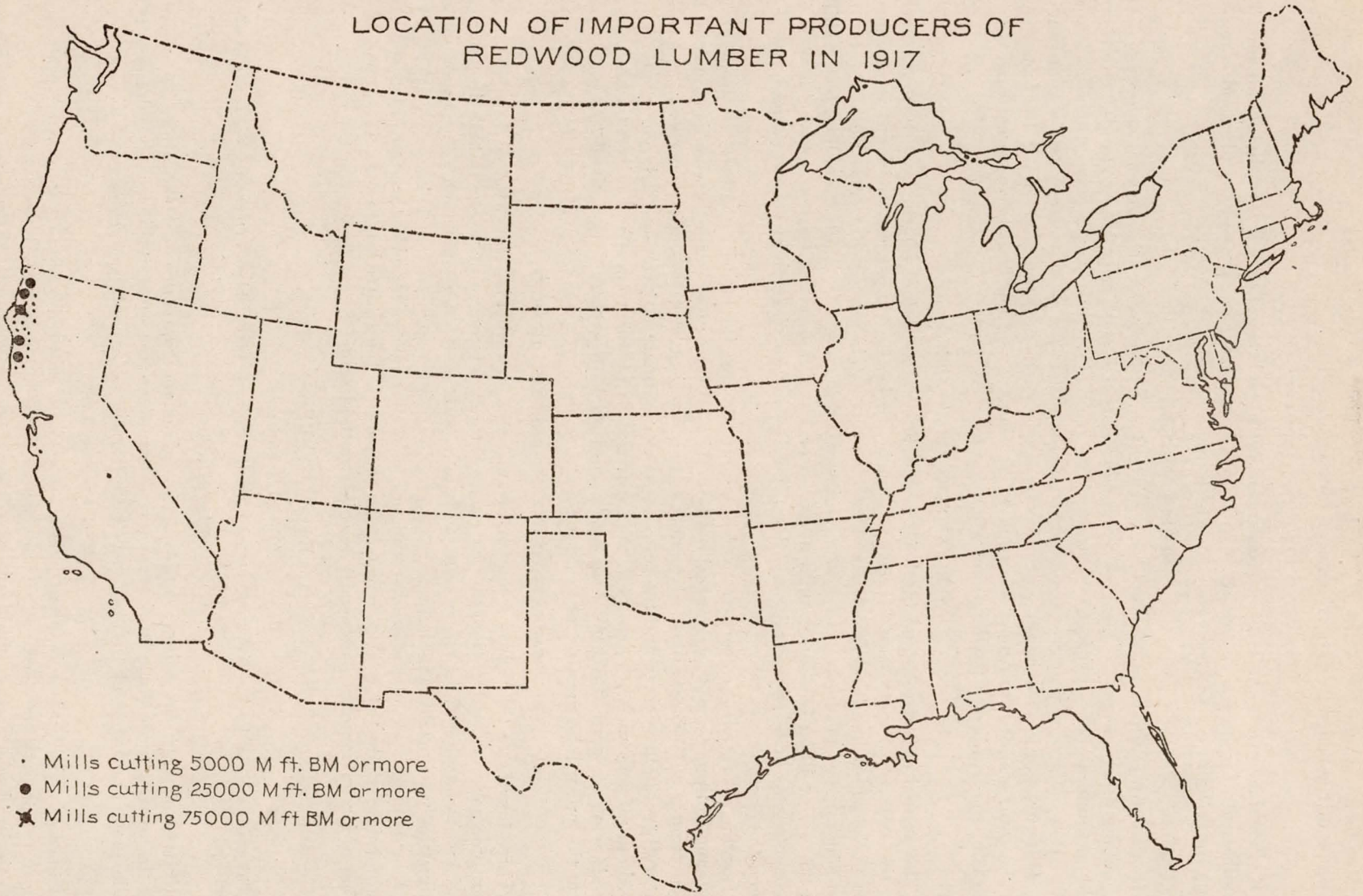
REDWOOD.

(*Sequoia sempervirens.*)

Bigtree (*Sequoia gigantea*) is included with the redwood in the discussion in this chapter.

DISTRIBUTION.

The redwood occurs in the coast belt of northern California from just below San Francisco Bay to the Coos Bay district of southern Oregon. The bulk of it is in Del Norte, Humboldt,


LOCATION OF IMPORTANT PRODUCERS OF
REDWOOD LUMBER IN 1917
· Mills cutting 5000 M ft. BM or more
● Mills cutting 25000 M ft. BM or more
✱ Mills cutting 75000 M ft BM or more

MAP No. 10

and Mendocino Counties, Calif. The bigtree, which is also sold as redwood, occurs on the west slope of the central Sierras over very limited areas.

USE IN AIRCRAFT.

Redwood is variable in its properties and is apt to be brash; hence it is probably not suitable as a substitute for spruce in aircraft. It is, however, an excellent wood for plywood cores on account of its lightness and the ease with which it can be worked.

SUPPLY OF TIMBER.

Redwood forms pure forests in northern California; farther south it occurs as groves scattered among other species. The trees reach enormous size, with very heavy stands. Redwood is seldom found above 3,000 feet elevation. Bigtree reaches even larger sizes than does redwood. It usually occurs in groves mixed with such other species as western yellow pine, sugar pine, white fir, and incense cedar, and is found at elevations between 5,000 and 8,400 feet.

The total stand of redwood is estimated at about 73 billion board feet, practically all of which is in the hands of a few large private owners.

PRODUCTION OF LUMBER.

The annual cut of redwood lumber has not fluctuated widely for the past 10 or 15 years from the average of approximately 500 million board feet. Almost the entire cut is produced by 34 mills, which handle redwood almost exclusively. The capacity of these mills is rated at about 850 million feet a year. In 1917, 18 mills reported cuts of from 5 to 25 million feet, 4 mills from 25 to 75 million feet, and 1 mill in excess of 75 million feet. Two of these mills were in the coast region below San Francisco Bay, one was in the Sierra bigtree region, and the rest were on the northwest coast.

Logging operations are carried on throughout the year in the redwood belt. All operators use steam equipment and logging railroads. Most of the upper-grade lumber is now cut in 16-foot lengths. While no particular effort is made to saw straight-grained material, redwood is naturally straight grained and the proportion of such material produced is large.

About 50 per cent of the cut is in the Clear and Sap Clear grades, and it is estimated that, after allowing for grain, pitch pockets, shake, and other defects, at least half of this, or 25 per cent of the cut, will be suitable for aircraft construction.

MARKETS AND USES FOR THE LUMBER.

Three-fourths of the redwood lumber produced by sawmills is used, without further manufacture, for general construction and for railroad ties. Planing-mill products take 19 per cent of the cut, wood pipe about 2 per cent, and tanks and silos almost as much. A great number of industries use smaller amounts.

A large proportion of the lumber and ties, as well as of the manufactured products, is used in California. Redwood is sold, however, in all parts of the United States and is shipped to a number of foreign countries, especially to those on the Pacific.

BALD CYPRESS.

(*Taxodium distichum.*)

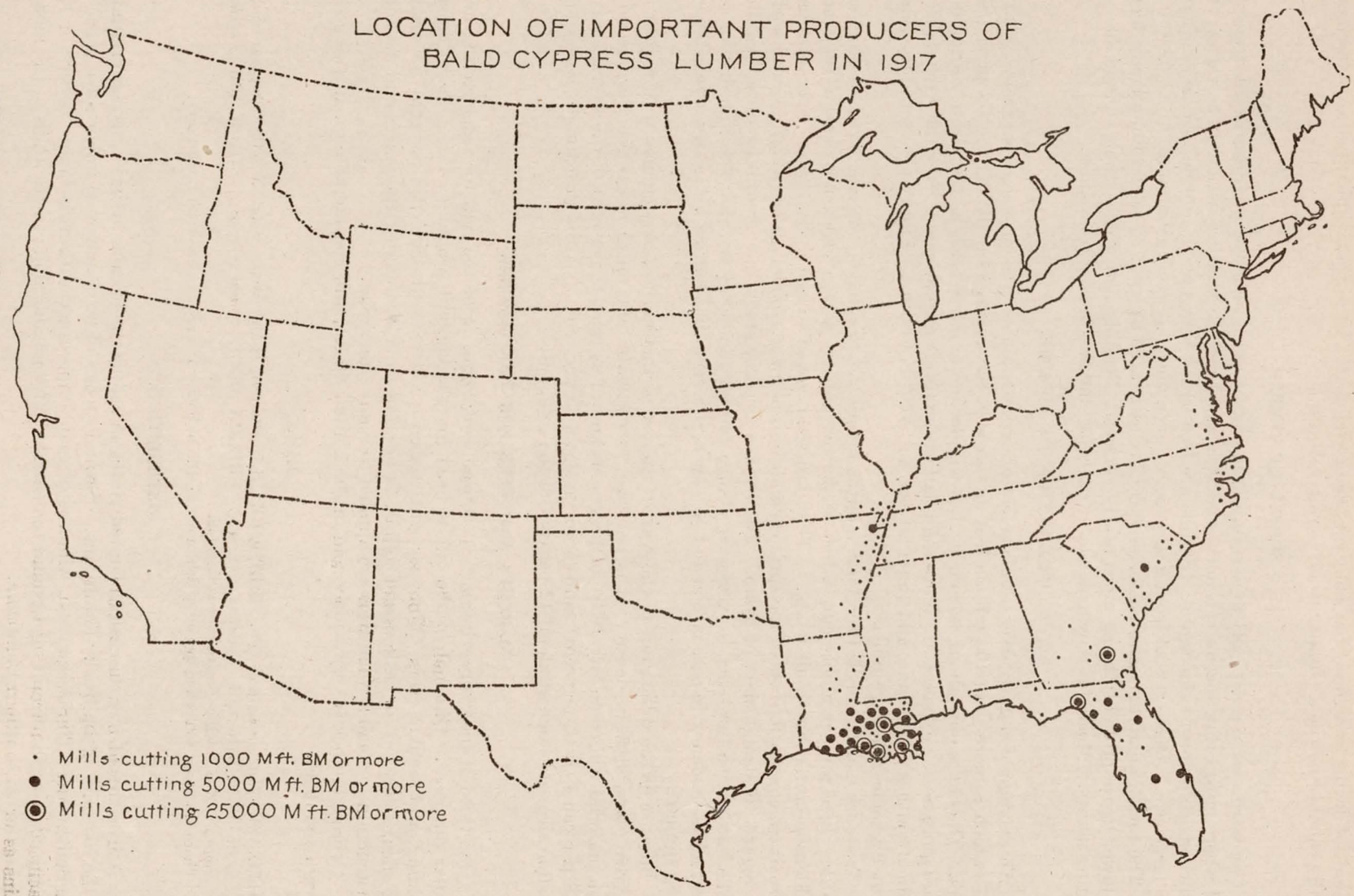
This species is also known as cypress, swamp cypress, southern cypress, black cypress, red cypress, and white cypress.

DISTRIBUTION.

Cypress occurs in the Atlantic and Gulf coastal regions from southern Delaware to Texas, and along the bottom lands of the Mississippi and its tributaries to southern Illinois and Indiana. It is best developed and most abundant in southern Louisiana (Atchafalaya region) and in Florida.

USE IN AIRCRAFT.

Cypress is slightly heavier than spruce. Carefully selected pieces are somewhat superior in strength to spruce when used in the same sizes. It is, however, greatly variable in its strength properties, and selection of suitable pieces is difficult on that account. Furthermore, satisfactory



MAP No. 11

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methods of drying and gluing have not yet been developed. Until these difficulties are overcome it will probably not be a popular wood for aircraft use.

SUPPLY OF TIMBER.

Cypress grows in practically pure stands or in mixture with tupelo over large areas of swampy land where most other species can not live. It is also found in mixture with a great variety of hardwoods common to the region. Stands are frequently very heavy, and mature trees are of very large size. Diameters of from 6 to 8 feet or even more are not uncommon.

The total remaining stand has been variously estimated at from 25 to 40 billion board feet, the lower figure probably being more nearly correct. Possibly half of the stand is available to existing plants. Most of it is owned in large units by land and lumber companies.

PRODUCTION OF LUMBER.

An average of slightly over a billion feet of cypress lumber was cut each year from 1913 to 1917, which is more than 100 million feet in excess of the average cut during the six preceding years. The cut is now about stationary, but will decline in a few years as the virgin supply becomes more nearly exhausted. More than half of the total cut now comes from the Atchafalaya Basin of southern Louisiana, and about 20 per cent is cut in Florida. Eighty per cent of the total is cut by some 205 large mills.

Trees are usually girdled for some months before they are felled, in order to make the logs lighter. Logs are commonly cut 16 feet or shorter, and are gotten together by means of steam skidders mounted on "pull boats." They are then towed to the mills. Some operators use railroad transportation where the surface conditions allow it. The logs are usually sawed without regard to straightness of grain. To produce airplane stock they should be sawed parallel to the bark, since the taper is excessive. Since cypress lumber is very hard to kiln-dry on account of its tendency to caseharden and to check, it is usually air-dried for nearly a year before being shipped.

Because of the difficulties in the way of the use of this species, particularly with regard to its great variability in density, it is not easy to estimate how much is suitable for aircraft. Such material will come largely from the grades known as tank (1 per cent of the average cut), A (8 per cent), B (7 per cent), and factory selects (5 per cent). A rough estimate places the possible airplane stock at about 12 per cent of the total cut.

MARKETS AND USES FOR THE LUMBER.

One-third of the cypress lumber cut is used as it comes from the mill for construction and similar purposes. One-half of the cut is used for planing-mill products—sash, doors, finish, molding, and similar uses. Four per cent is used for boxes and crates, 3½ per cent for tanks and silos, 2 per cent for caskets and coffins, 1½ per cent each for laundry appliances and machine construction. Smaller quantities are applied to many other uses.

Cypress lumber is very widely sold in the United States, and considerable quantities go to foreign countries.

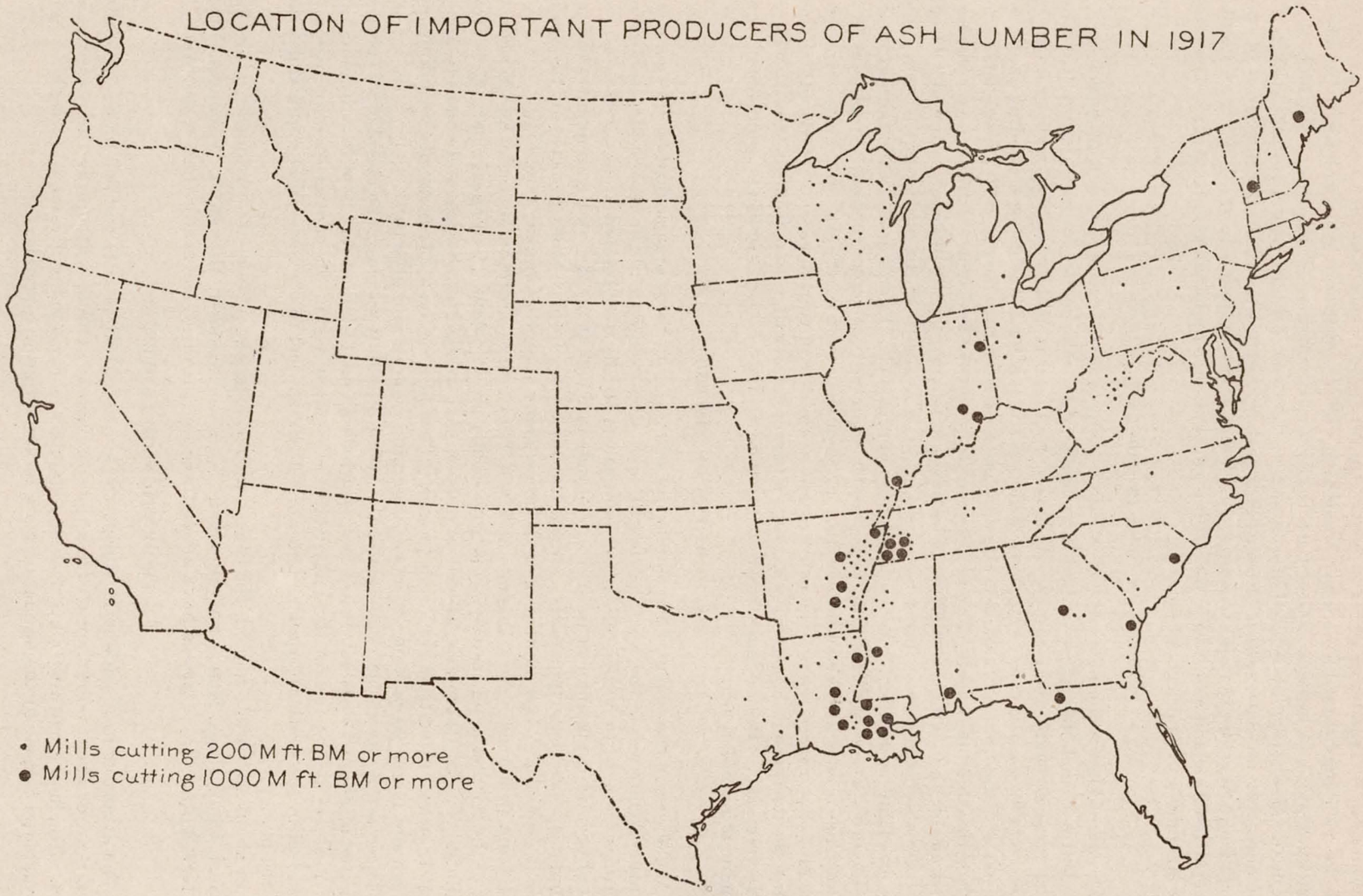
ASH.

WHITE ASH (*Fraxinus Americana*). BILTMORE ASH (*Fraxinus biltmoreana*). GREEN ASH (*Fraxinus lanceolata*). PUMPKIN ASH (*Fraxinus profunda*). OREGON ASH (*Fraxinus oregona*). BLACK ASH (*Fraxinus nigra*). BLUE ASH (*Fraxinus quadrangulata*).

There are about ten other species of ash, none of which, however, are of commercial importance.

DISTRIBUTION.

Ash occurs all over the eastern United States and along the streams in the Plains region almost to the foothills of the Rocky Mountains. Several species of no commercial importance occur in the Southwest. The Oregon ash, which is of some importance within its range, occurs in the Pacific coast region from Puget Sound to central California and along the foothills of the mountains as far as southern California.


LOCATION OF IMPORTANT PRODUCERS OF ASH LUMBER IN 1917
• Mills cutting 200 M ft. BM or more
● Mills cutting 1000 M ft. BM or more

MAP No. 12

White ash is common in all States east of the Mississippi, except in the Coastal Plain region, but is not very important in the lower Mississippi valley. Biltmore ash is chiefly in Tennessee, Kentucky, Ohio, and Indiana. Green ash is of greatest commercial importance in the bottomlands of the Mississippi and its tributaries and in the Coastal Plain region. Pumpkin ash is of importance only in southeastern Missouri and eastern North Carolina. Oregon ash is of some importance in Washington and Oregon. Black ash is chiefly found in the Lake States and in northern New England and New York. Blue ash is of some importance in Kentucky, Tennessee, Indiana, Ohio, and southern Missouri.

USE IN AIRCRAFT.

The ashes known commercially as "white ash" include both white ash and green ash, as well as the Biltmore and blue ashes. All of these are very desirable woods for use in aircraft. White ash has great strength and stiffness, bends very well, and is usually fairly straight grained. It is used very extensively for longerons, bent work on wings and fuselage, landing skids, and other parts of the framework of aircraft, and has been used to some extent for propellers. Second-growth ash is more likely to have the requisite density and hence is frequently considered more desirable than old-growth ash for those uses in which great toughness is required. Oregon ash is probably as good as white ash. Black ash is not so stiff as the others, but is very tough and is excellent for bending. It should make good plywood. Pumpkin ash is lighter and weaker than the other ashes, and therefore, is not desirable for airplane construction. Northern-grown white ash has been considered more satisfactory than that from the South, probably on account of the fact that a large part of the ash now cut in the North is from second-growth stands, and because the northern ash has on the average a higher density than that from the South, which is largely green ash. In the South brash material of the better species of ash is usually sold under the name of pumpkin ash.

SUPPLY OF TIMBER.

Ash occurs in mixed hardwood stands and seldom forms more than a small proportion of the mixture. White ash in the North ordinarily makes up from 5 to 10 per cent of old stands, and sometimes from 20 to 50 per cent of second-growth stands over limited areas. Green ash is a more important component of most of the stands in which it occurs, and is frequently the predominant species in certain parts. Black ash makes up from 1 to 10 per cent of the stands where it grows, and over limited areas is occasionally the predominant tree.

Except in northern New England and New York and in northern Michigan and Wisconsin, most of the northern and eastern ash is from second-growth stands, and a large part of it is from woodlots. The Southern ash, as well as some of that in the Lake States, still comes to a large extent from extensive tracts in virgin forests. The old-growth supply is rapidly dwindling, and a larger and larger proportion of the cut is coming from second growth.

There are no available estimates of the stand of ash by species. The total of all species is estimated at about 10½ billion board feet, of which about 1½ billion feet is in New England and New York, 1½ billion feet in the Lake States, 1½ billion feet in the central woodlot region, 1½ billion feet in the southern Appalachians, and 4½ billion feet in the lower Mississippi valley and Gulf region.

In about the order named, the States with the largest stands are: Arkansas, Louisiana, Missouri, Ohio, Texas, Mississippi, Michigan, Tennessee, Georgia, Minnesota, Wisconsin, Maine, and New York. These States have about three-fourths of all the ash in the United States.

PRODUCTION OF LUMBER.

The average cut of ash lumber during the five years 1913 to 1917 was just under 200 million feet a year, or about 50 million feet less than the average annual cut during the preceding six years. The lumber cut is steadily declining and may be expected to do so until it reaches a figure approximately equal to the annual increase of second-growth stands.

Besides the ash cut in the form of lumber, much of the handle and vehicle stock is cut directly from logs or bolts, from 25 to 35 million feet is used for slack cooperage, and 2 or 3 million feet is made into veneer. In normal times from 5 to 7 million feet of ash logs is cut for export.

Arkansas and Louisiana are now the leading States in the production of ash, and together they produce one-fourth of all the ash lumber cut in the United States. Following them, come Wisconsin, Tennessee, Indiana, Mississippi, New York, and Michigan. These States together produce about 60 per cent of the total. Twenty-nine mills reported cuts in 1917 of more than one million feet of ash. Two of these were in northern New England, 3 in Indiana, 5 in the southern coastal region, and the rest in the lower Mississippi valley. Ash lumber is cut in smaller amounts by a very large number of both large and small mills.

Logging in most of the ash regions is carried on throughout the year, except that in the river bottoms it is usually interrupted by high-water periods. Steam logging is sometimes employed, but animal logging is used by most operators. Logs are carried to the mills by rafts, railroads, teams, or motor trucks, according to the region in which the operations are conducted. Logs are usually cut in lengths of 16 feet or less. Many operators use considerable care to saw straight-grained lumber, particularly from the white ashes, since so many of the uses to which high-grade ash is put require straightness of grain.

The strongest material is usually sawed from within 7 inches of the center of the trees; consequently, trees of comparatively small diameters may produce as much airplane material as trees from virgin stands. The proportion of high-grade material produced varies, of course, with the size of the trees as well as with the locality where they grow. From second-growth white ash stands, trees under 10 inches in diameter yield no firsts and seconds, and about 50 per cent No. 1 common; trees 20 inches in diameter yield over 40 per cent firsts and seconds, and about 35 per cent No. 1 common. Assuming the average diameters to be from 14 to 16 inches, an average proportion is about 25 per cent firsts and seconds, and 42 per cent No. 1 common.

MARKETS AND USES FOR THE LUMBER.

Practically all of the ash lumber cut is further manufactured before it reaches the consumer. Approximately 22 per cent is used for handles, especially those for spades, shovels, hoes, rakes, and forks, for which long, stiff, tough, straight-grained pieces are required. More ash than any other wood except hickory is used for handles. Twenty per cent of the cut is used for butter tubs. This material is nearly all green and black ash, and comprises short, clear lengths cut from low-grade logs. Fifteen per cent is used in vehicle manufacture, for such parts as poles, tongues, axles, and felloes, which require tough white or green ash of high quality, and for bodies, which are made of larger pieces of old-growth ash. Planing-mill products take 7 per cent of the cut, much of it black ash. Refrigerators and kitchen cabinets (mostly black ash), furniture (mostly black ash), car construction (all species) each take about 6 per cent of the cut. Agricultural implements and oars (both of which require high-grade white and green ash) each take about 3 per cent. Athletic goods, musical instruments, fixtures, hames, and many other products that call for a good grade of material take smaller amounts.

Ash is either manufactured into the finished product near where it is cut or is shipped to the centers of the wood-manufacturing industry in the Northern and Eastern States. Several million feet of logs is normally exported to Europe each year and several million feet of lumber goes to Europe and to South America.

BASSWOOD.

(*Tilia americana.*)

This species is also called linden, linn, and whitewood. Downy basswood (*T. pubescens*) and white basswood (*T. heterophylla*) should probably also be grouped with the common basswood. Data are not available, however, with respect to the strength of these species.

DISTRIBUTION.

Basswood occurs from northern New Brunswick to Lake Winnipeg, south to Virginia, northern Georgia and Alabama, eastern Texas, and as far west as eastern Dakota, Kansas, and Oklahoma. It reaches its largest size in the lower Ohio River bottom lands, but is more abundant northward.

USE IN AIRCRAFT.

Basswood is light in weight but low in strength; consequently it is not a good substitute for spruce. It is, however, one of the best woods in ability to take nails without splitting, and is excellent for webs of wing ribs and for plywood cores generally. It is also used for thin flooring plank.

SUPPLY OF TIMBER.

Through most of its range basswood is found in mixture with other hardwoods. In the North it frequently is the predominating species in the stand, and sometimes forms pure stands over limited areas. Mature trees frequently reach diameters of from 3 to 4 feet and heights of more than 100 feet. While much of the basswood is in situations in which logging can be done with little difficulty, a considerable part of it is in localities as yet undeveloped and is not available to existing mills.

The total stand is estimated at approximately 9 billion board feet, of which 80 per cent is in Wisconsin, Michigan, Minnesota, Iowa, New York, Kentucky, West Virginia, and Vermont, in the order named. There is about 1⅓ billion feet in New England and New York, 5 billion feet in the Lakes States, 1½ billion feet in the southern Appalachians, and 1 billion feet in the central wood-lot region.

Much of the virgin stand, which is in northern New England, the Lake States, and the southern Appalachians, is owned by large land and lumber companies. Outside of these three regions, most of the basswood is in small holdings.

PRODUCTION OF LUMBER.

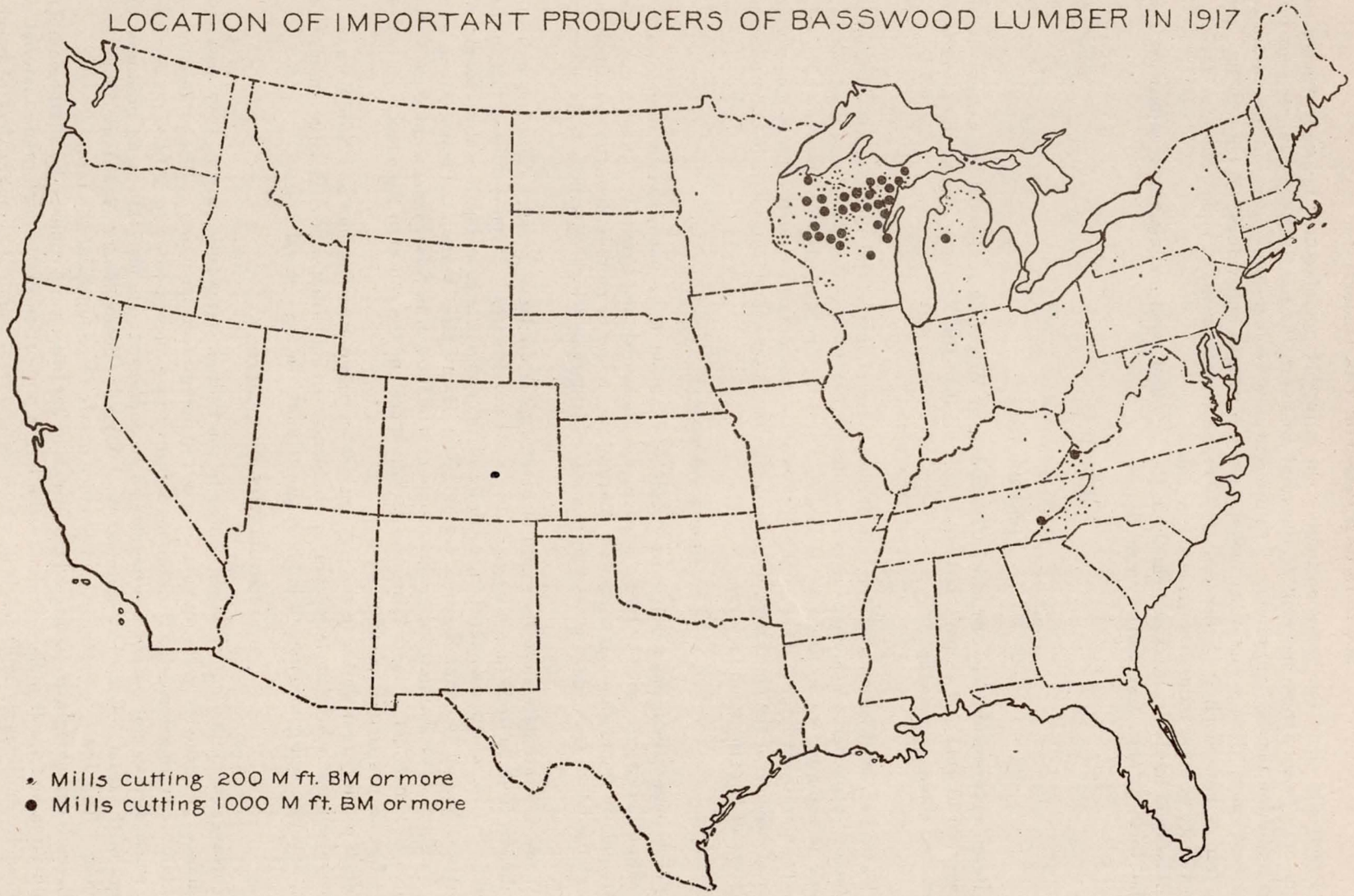
For the five-year period 1913 to 1917, the average annual cut of basswood lumber was approximately 250 million board feet, which was nearly 100 million feet less than the average cut during the preceding six years. The general tendency indicates a steady decline as the accessible virgin supplies become more nearly exhausted. One-third of the total is cut in northern Wisconsin, one-fifth in Michigan, and one-eighth in West Virginia. These States, with New York, cut about three-fourths of the total.

From 95 to 99 per cent of the basswood cut in Michigan and Wisconsin and the larger part of that cut in West Virginia is produced by large mills. In 1917, 32 mills reported cuts of more than a million feet of basswood, and about 180 reported cuts of between 200 thousand and a million feet. Basswood was cut along with a variety of other woods by all of these mills and formed only a minor part of the total output of most of them.

Logging operations proceed the year round in most of the basswood region. Animals are quite generally used, although a few companies log with steam. The large operations in the Lake States and in the South are railroad operations. Logs are commonly cut 16 feet or less in length. Mills cut for grade, but not particularly for straight grain. Some 10 million feet of basswood veneer is cut each year.

It is estimated that from 16 to 20 per cent of the basswood cut will grade firsts and seconds, and that from 22 to 25 per cent will grade No. 1 common. The proportions will probably run a little higher in the South, where the trees are somewhat larger. Material suitable for aircraft construction will come from these grades, principally from the first,

LOCATION OF IMPORTANT PRODUCERS OF BASSWOOD LUMBER IN 1917



MAP No. 13

MARKETS AND USES FOR THE LUMBER.

Practically all of the basswood lumber cut is further manufactured before it reaches the consumer. Twenty-three per cent of the total goes into the box industry; 16 per cent into finish and other planing mill products; 16 per cent into woodenware; 9 per cent into furniture; 6 per cent (more than of any other one species) into trunks and valises; 5½ per cent into picture frames and molding; 3 per cent into musical instruments; 2½ per cent into toys. A wide variety of other industries use lesser amounts.

Basswood lumber is marketed chiefly in the region of wood-manufacturing industries, that is, the North Atlantic and North Central States.

BEECH.

(*Fagus atropunicea.*)

DISTRIBUTION.

Beech occurs from New Brunswick to northern Wisconsin and south to eastern Texas and western Florida. It reaches its best development in the Northern States, the lower Ohio Valley and the Appalachians.

USE IN AIRCRAFT.

Having strength properties very similar to those of maple and birch, it makes a fairly satisfactory propeller wood where requirements are not too exacting, and was used for this purpose to some extent in Europe. It is also a satisfactory material for plywood. Because of the comparatively large and accessible supplies of the timber fairly close to centers of consumption, and because of the cheapness of the material, beech may be of considerable importance in the future of airplane manufacturing.

SUPPLY OF TIMBER.

Beech sometimes forms nearly pure stands over limited areas, but is usually found in mixture with other species, such as birch, sugar maple, basswood, and hemlock. In such mixtures it is frequently the predominant species. Mature trees 3 feet or more in diameter are common. Most of the beech is in fairly accessible regions, in situations which offer no serious difficulty in logging.

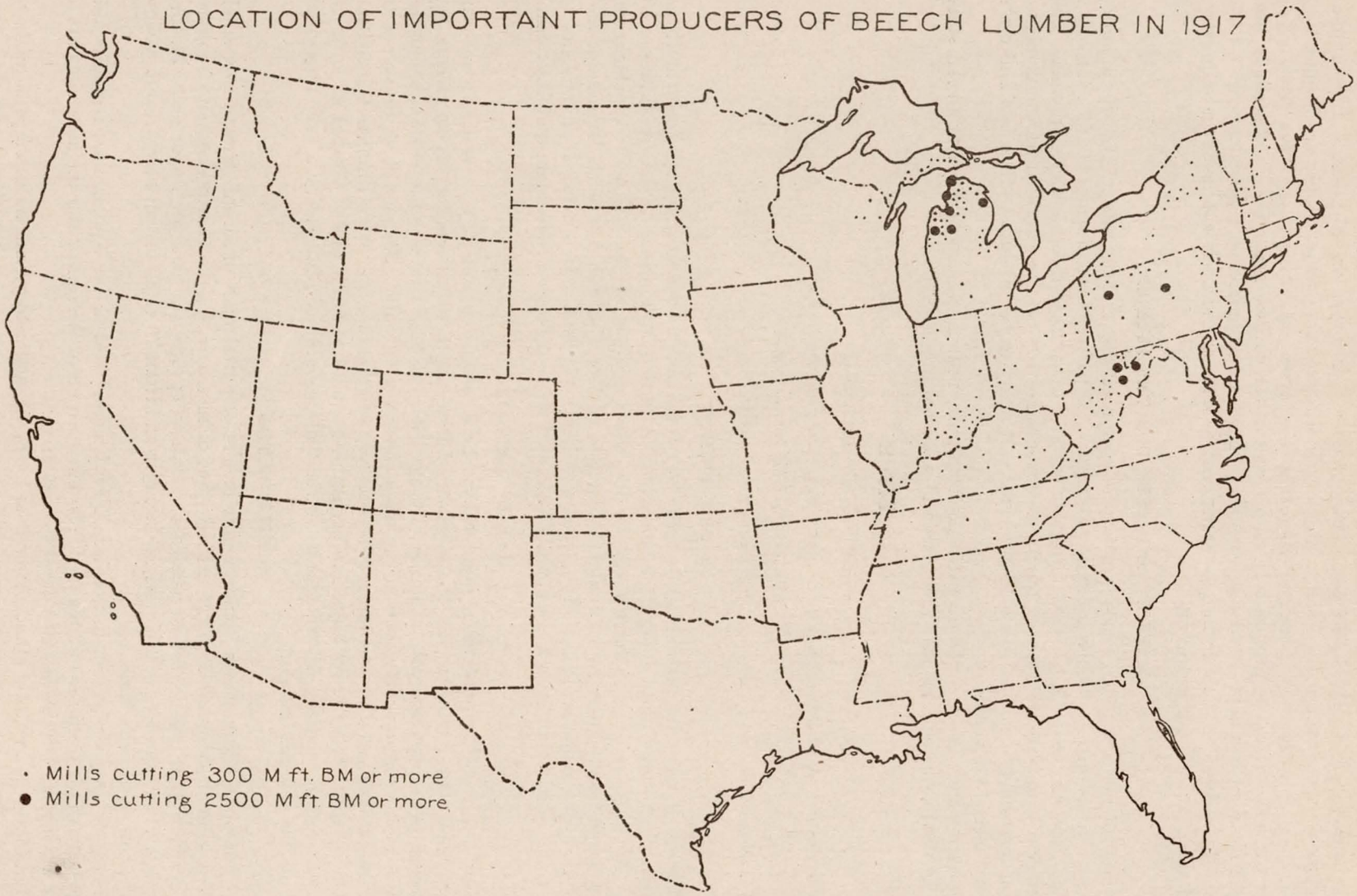
While accurate data as to the stand of beech timber are lacking, rough estimates indicate that there is from 20 to 25 billion board feet in the United States. Seven-eighths of it is in the following States, which are named in the order of their importance as beech States: Michigan, New York, Maine, Indiana, Kentucky, Ohio, New Hampshire, Vermont, Pennsylvania, and West Virginia. It is estimated that there is about 8 billion feet in New England and New York, 4 billion feet in Michigan and Wisconsin, 5 billion feet in the southern Appalachians, and 4 billion feet in the central woodlot region.

Much of the virgin timber in the Lake States, northern New England and New York, and the Appalachians is held by large lumber companies or land companies. A large amount of beech, however, is found on small holdings, particularly in the Central States.

PRODUCTION OF LUMBER.

The average annual cut of beech lumber in the United States from 1913 to 1917, was 350 million feet. For the six years previous it was 440 million feet per year. The production of beech lumber is, therefore, slowly declining and may be expected to do so until it reaches the point where it does not exceed the increase in second-growth stands. Michigan produces 20 per cent of the total, followed by Indiana, West Virginia, Pennsylvania, New York, Ohio, and Kentucky. The first five States named produce nearly three-fouths of the total.

Beech is cut, along with associated hardwoods or hardwoods and conifers, by a large number of both large and small mills. Probably the larger proportion of the high-grade material is produced by fairly large mills, each of which cuts several hundred thousand feet of beech.


LOCATION OF IMPORTANT PRODUCERS OF BEECH LUMBER IN 1917
· Mills cutting 300 M ft. BM or more
● Mills cutting 2500 M ft. BM or more

MAP No. 14

There are only about a dozen mills that cut more than 2½ million feet of beech apiece. Horse logging is the rule in the beech territory, although a few large operators use steam. Both animal and railroad transportation are used, and, where roads are good, motor trucks are coming into use to carry logs to the mill. Logging operations are carried on during most of the year.

In the Lake States, approximately 12 per cent of the cut will grade firsts and seconds, and 23 per cent No. 1 common. Possibly the Ohio valley and Appalachian timber may run a little better. It is estimated that from 5 to 10 per cent of firsts and seconds can be cut into quarter-sawed stock suitable for propellers.

MARKETS AND USES FOR THE LUMBER.

About 65 per cent of the beech lumber produced is further manufactured. Of this amount, 13.5 per cent is made into planing mill products; 11.2 per cent into furniture and chairs; 3.9 per cent into handles; 3.3 per cent into woodenware; 2 per cent into laundry appliances, and 1.5 per cent into brushes. Lesser quantities are utilized for vehicles, agricultural implements, musical instruments, spools and bobbins, tops, and many other products. The box and crate industry uses 18.3 per cent.

On the whole, beech lumber is generally sold quite near the place where it is produced, since much of the beech region is also the section of woodworking industries.

BIRCH.

SWEET BIRCH (*Betula lenta*).

This species is also known as black birch, cherry birch, and mahogany birch.

YELLOW BIRCH (*Betula lutea*).

This species is also known as silver birch, swamp birch, and gray birch.

DISTRIBUTION.

The range of sweet birch extends from Newfoundland to western Ontario, central Iowa, southern Illinois, and south along the Appalachian Mountains to Florida. While most abundant in the North, it reaches its largest size on the western slopes of the southern Appalachians. Yellow birch occurs from Newfoundland to northern New England, northern Minnesota, and south along the Appalachians to Tennessee and North Carolina. It is most abundant and of largest size in northern New England and New York, and in northern Michigan and Wisconsin.

USE IN AIRCRAFT.

Birch of these two species is quite heavy, hard, stiff, and resistant to wear, of uniform texture, and takes a fine finish. It, therefore, makes satisfactory propellers except where the requirements are exceptionally exacting. It has been used for propellers in several countries.

Birch plywood is widely used in the manufacture of aircraft. Because of its resistance to wear, its stiffness, and ease of bending, it is especially good for face ply where thinness is essential.

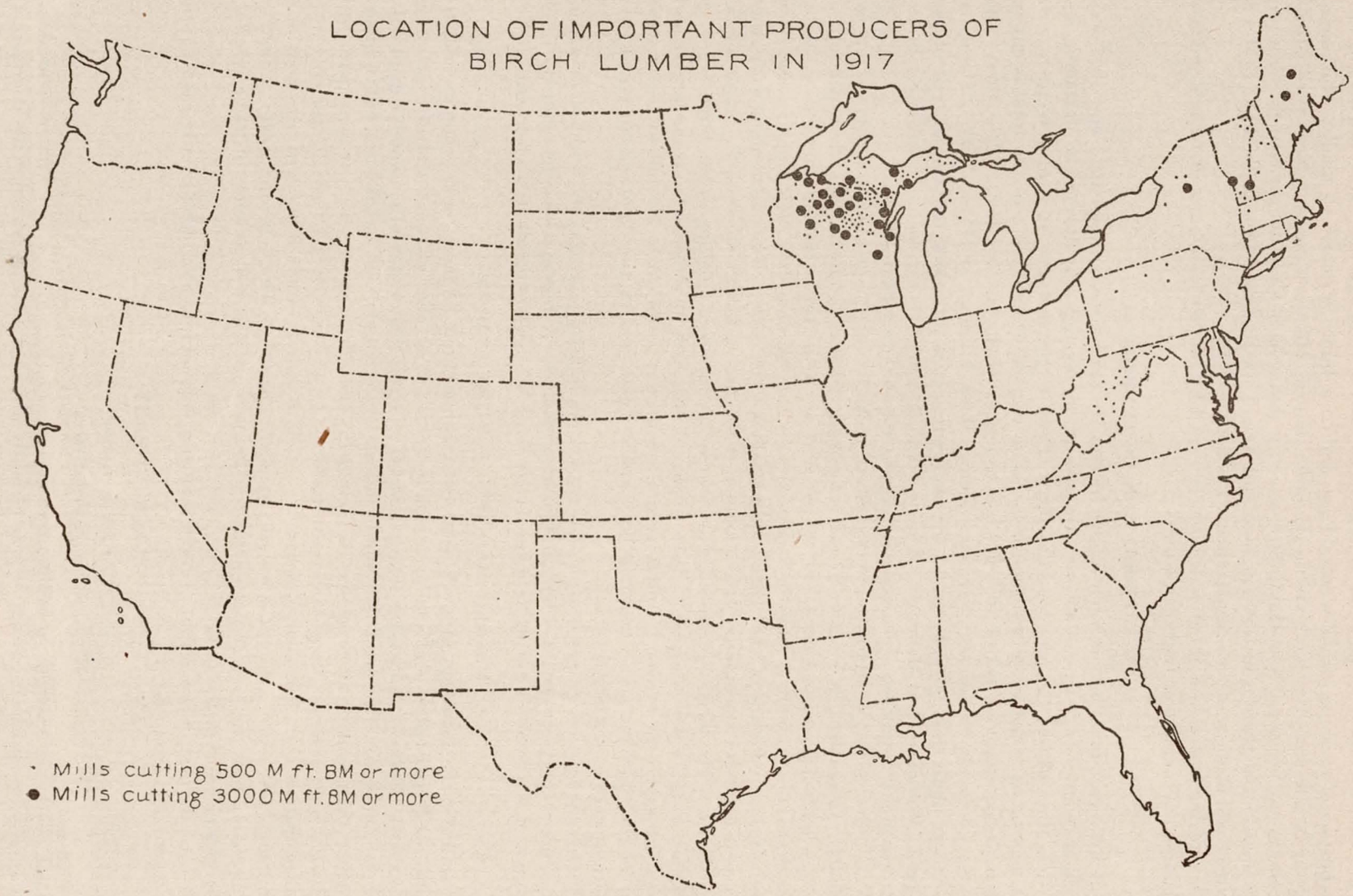
On account of the fairly large and accessible supplies of birch timber located at no great distance from the centers of manufacture, birch will probably continue to be a very important wood in the aircraft industry.

SUPPLY OF TIMBER.

While birch is frequently found in pure or almost pure stands of second growth over small areas, it seldom so occurs in virgin stands, but is mixed with other hardwoods and conifers, among which sugar maple, beech, basswood, hemlock, spruce, and pine are important. Mature sweet birch trees run from 2 to 3 feet in diameter and from 70 to 80 feet in height, while yellow birch averages a little larger.

Much of the virgin birch in northern New England and in the Appalachian region is still somewhat distant from sawmill plants. The birch region of Wisconsin and the adjacent part of upper Michigan is the most fully developed at present.

Estimates of the total stand of birch are very unsatisfactory, and no attempt is made to distinguish the species. The best available figure for all the birches together is approximately


LOCATION OF IMPORTANT PRODUCERS OF
BIRCH LUMBER IN 1917
· Mills cutting 500 M ft. BM or more
● Mills cutting 3000 M ft. BM or more

MAP No. 15

19 billion board feet. This includes several species other than the two under discussion, but the proportion of these (principally paper birch and river birch) is relatively small. The States having the largest stands of birch are, in the order named: Maine, Wisconsin, New York, Michigan, Minnesota, Vermont, New Hampshire, which together have about 90 per cent of the total. It is estimated that there is in New England and New York 10 billion feet, in the Lake States 8 billion feet, and in the southern Appalachians 1 billion feet.

The greater part of the old-growth birch is owned by lumber companies or by land-investment companies, in large or fairly large units.

PRODUCTION OF LUMBER.

The average annual cut of birch lumber in the United States between 1913 and 1917 was 440 million board feet. This is a little in excess of the average cut during the preceding six years. In other words, the production of birch is yet on the increase, and the present rate of output may be expected to be maintained for some years to come. Half of the total is cut in northern Wisconsin, and two-thirds in Wisconsin and Michigan together. After these, the important producing States are: Vermont, Maine, West Virginia, and New York. These six States report more than 90 per cent of the total cut. It is estimated that 85 per cent of the birch cut in Wisconsin and Michigan is yellow birch, and most of the remainder is sweet birch. This proportion is doubtless approximately correct for the other States named.

While birch is cut by a large number of small mills, by far the greater proportion is cut by large mills. In northern Minnesota 97 per cent of the total is produced by mills which cut in excess of a million board feet each, and 99 per cent of the northern Michigan output is cut by mills of that class. About 22 mills in Wisconsin and Michigan and 6 in New England and New York report the production of more than 3 million feet of birch each. Birch is cut along with other species as it comes in the stand. Horse logging is the rule, although some of the larger operators use steam. The largest producers run railroad operations. Logging in the birch region is carried on during most of the year. Birch lumber is ordinarily plain sawed and the largest and best logs are saved for veneer. Under normal conditions, from 25 to 30 million feet a year is used for this purpose. The big mills both in the North and in the Appalachian region use considerable care in grading their lumber.

It is estimated that 12 per cent of the cut will grade firsts and seconds, 8 inches or wider, and that possibly 3½ per cent will be suitable for propellers. Firsts and seconds make up 14 or 15 per cent of the total output in the Lake States, and No. 1 common about 25 per cent.

MARKETS AND USES FOR THE LUMBER.

Practically the entire cut of birch is further manufactured. Planing-mill products, including finish, sash and doors, and similar products, take 28 per cent of it. Furniture including chairs, takes 17.7 per cent and uses a larger quantity of birch than of any other woods except oak, maple, and red gum. The spool and bobbin industry uses 6.9 per cent of the birch cut, a quantity greater than that of all other woods combined. Of all birch cut, 6.1 per cent goes into woodenware and novelties; 3.2 per cent into fixtures; 3 per cent into vehicles; 2.7 per cent into musical instruments; 2.1 per cent into handles; 1.7 into dowels; and 1.6 per cent into boot and shoe findings. Many other industries use smaller amounts. The box and crate industry, which probably uses the greater part of the low-grade lumber as well as some of higher grades, absorbs 18.9 per cent of the total.

The greater part of the output of birch lumber is sold and used in regions fairly close to the places where it is produced.

BLACK CHERRY.

(*Prunus serotina*).

DISTRIBUTION.

Black cherry occurs from Nova Scotia to Dakota, south to Florida and Arizona, and along the mountains to South America. It was formerly abundant and of considerable commercial importance in the Appalachian region from West Virginia to Alabama, but is nowhere abundant now.

USE IN AIRCRAFT.

Cherry wood is strong, fairly hard, straight grained, works well, and takes a fine finish, consequently it is an excellent propeller wood. It is also good for plywood facing. The supply is so small, however, that this species can probably never be of great importance to the airplane industry.

SUPPLY OF TIMBER.

Available estimates of the supply of standing black cherry timber are only rough guesses based on the amounts known to exist in a few localities. There is supposed to be between 400 and 500 million feet all together. Cherry usually occurs scattered as single trees in mixed hardwood forests and along roads and fences. It is estimated that about 100 million feet is in New England and New York, 200 million in the southern Appalachians, and 100 million in the central woodlot region. Probably there is more cherry left in West Virginia than in any other State. New York, Pennsylvania, Ohio, Michigan, Tennessee, North Carolina, and Kentucky are also supposed to have considerable quantities. A few large virgin tracts in the mountains still contain considerable amounts of cherry, but by far the greater part of the supply is in the hands of a multitude of small owners.

PRODUCTION OF LUMBER.

The average annual cut of black cherry lumber in recent years has been less than 10 million board feet, and it is steadily decreasing. West Virginia cuts the most. Other States that produce considerable quantities are: Pennsylvania, New York, North Carolina, Indiana, Tennessee, Michigan, Ohio, and Virginia. About 20 States in all report some cherry cut.

Cherry forms only a very small part of the cut of most of the mills that saw it. It is cut by a large number of both large and small mills, very few of which cut large quantities.

It is estimated that from 15 to 25 per cent of the cut grades firsts and seconds, most of which would be suitable for propellers.

USES FOR THE LUMBER.

Cherry is a valuable cabinet wood, and practically the entire cut is further manufactured. Eighteen per cent goes into fixtures. Seventeen per cent goes into printing material (backing) this industry using more cherry than any other five woods combined. Car construction uses for finish 16 per cent of the cherry lumber cut. Fourteen per cent goes into planing-mill products; 6 per cent into professional and scientific instruments; 5½ per cent into furniture; 5 per cent into handles; 4 per cent into brushes. Musical instruments, clocks, boats, fancy boxes, and patterns take considerable quantities.

ELM.

CORK ELM (*Ulmus racemosa*).

This species is also known as rock elm, cork-bark elm, and hickory elm.

WHITE ELM (*Ulmus americana*).

This species is also known as American elm, water elm, and gray elm.

SLIPPERY ELM (*Ulmus pubescens*).

This species is also known as red elm and rock elm.

WING ELM (*Ulmus alata*).

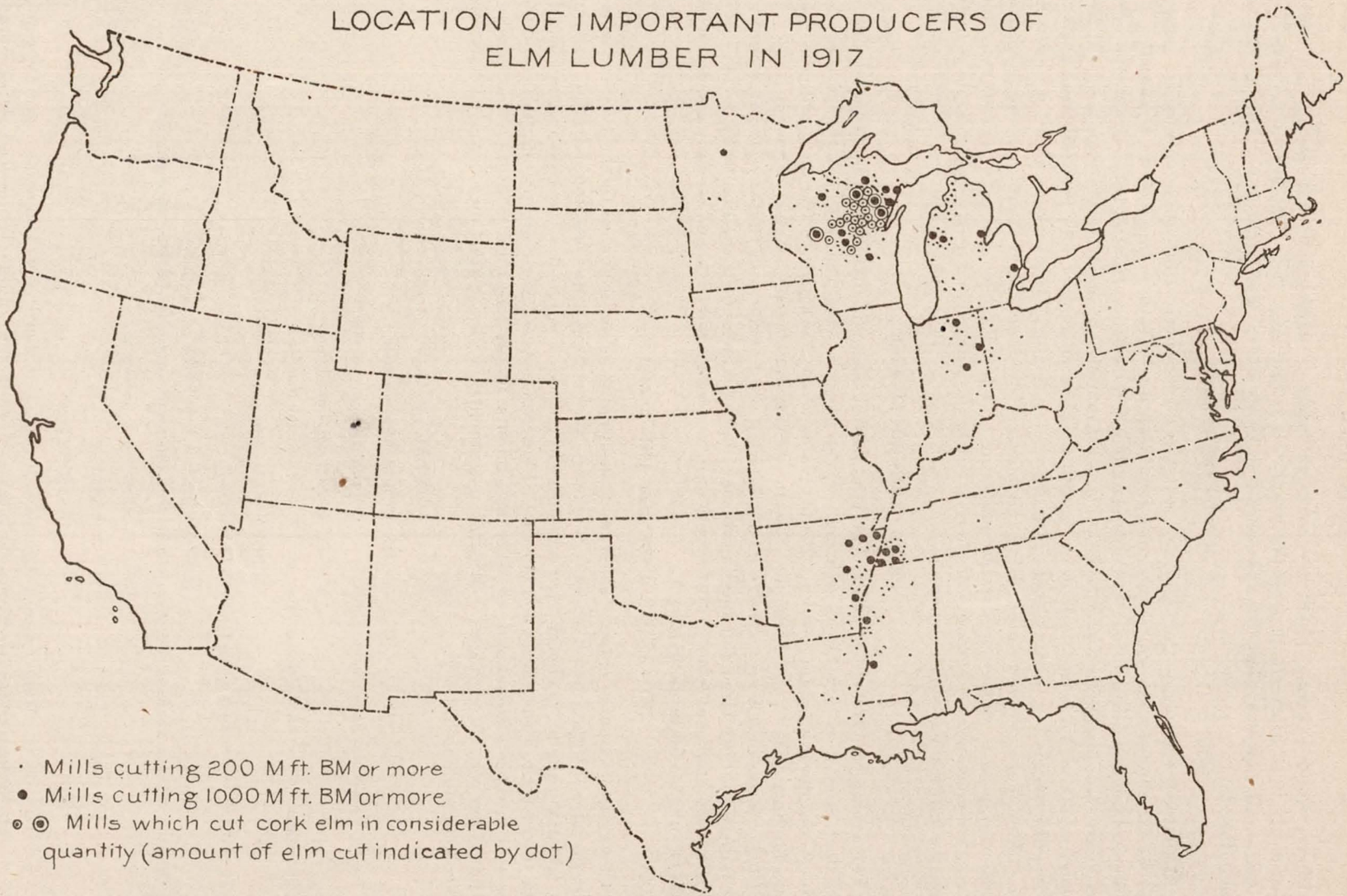
This species is also known as wahoo, witch elm, cork elm, small-leaved elm, red elm, water elm, and mountain elm.

CEDAR ELM (*Ulmus crassifolia*).

This species is also known as red elm and basket elm.

DISTRIBUTION.

Cork elm occurs from eastern Quebec, through northern New Hampshire and Vermont, to Michigan, Wisconsin, northeastern Nebraska, Missouri, and middle Tennessee. It is commercially important chiefly in northeastern Wisconsin and adjacent parts of upper Michigan. White


LOCATION OF IMPORTANT PRODUCERS OF
ELM LUMBER IN 1917
· Mills cutting 200 M ft. BM or more
● Mills cutting 1000 M ft. BM or more
⊙ ◉ Mills which cut cork elm in considerable quantity (amount of elm cut indicated by dot)

MAP No. 16

elm occurs from southern Newfoundland to the eastern base of the Rocky Mountains and south to Texas and Florida. Commercially it is most important in Michigan, Wisconsin, Indiana, and the lower Mississippi Valley. Slippery elm has almost the same range as white elm, but does not extend quite so far north or south. Wing elm occurs in the Atlantic coast region from southern Virginia to Florida, and in the lower Mississippi and tributary valleys from southern Illinois to Texas. Cedar elm occurs from Mississippi through Louisiana, southern Arkansas, and most of the wooded part of Texas.

USE IN AIRCRAFT.

Elm is slightly heavier than ash and rather low in stiffness but very tough and shock resistant. It steam bends very well and may be substituted for ash in longerons and for similar uses. It is also used for other bent work, such as landing skids and flying-boats' keels. Cork elm has been approved for propellers. White elm is used for bent plywood.

Individual pieces of slippery and white elm of the same density as cork elm have the same properties; therefore, the species is a less important consideration than the density. Slippery elm is on the average lighter than cork elm, and white elm is lighter and less stiff. All of the elms require care in drying because of their tendency to warp and to twist.

The supply of cork elm being very limited, this species probably has no future as a propeller wood. On the other hand, the supply of all the elms taken together is comparatively large and accessible, and growth is rapid; therefore, elm for bent work and plywood may be used in increasing quantities.

SUPPLY OF TIMBER.

Elm grows scattered in mixed stands with other hardwoods, and does not form pure stands. It is a very common and widely distributed field and roadside tree. White elm reaches diameters of 6 feet or more at maturity. Cork elm occasionally reaches diameters of 3 feet, while slippery elm and cedar elm are somewhat smaller, and wing elm is rarely 2 feet in diameter. Forest-grown cork elms are frequently free of branches for 60 feet from the ground.

Such estimates as are available of the total stand of elm do not separate the species. It is judged that there is about 16 billion feet of elm standing. The States with the largest supplies of elm are, in the order named: Arkansas, Missouri, Michigan, Louisiana, Mississippi, and Wisconsin. These six States have two-thirds of the total stand. In New England and New York there is slightly less than 1 billion feet, in the Lake States nearly 4 billion feet, in the Mississippi valley 8 billion feet, and in the central woodlot region 3 billion feet. It has been estimated that from one-fourth to one-third of the elm cut in Wisconsin, 5 per cent of that cut in lower Michigan, and 20 per cent of that cut in upper Michigan is cork elm. There is probably about 300 million feet of cork elm standing in these States, which have nearly all of the supply of this species that is commercially important. While most of the remaining forest-grown elm, and probably practically all of the forest-grown cork elm is in large holdings owned by land and lumber companies, a large part of the total stand of elm is held by small owners. Much of it, especially in the lower Mississippi region, is on land that will be cleared for agriculture.

PRODUCTION OF LUMBER.

During the years 1913 to 1917 the average annual cut of elm lumber was about 215 million feet, which is 60 million feet less than the average cut during the preceding six years. The cut is gradually but quite steadily decreasing. Wisconsin and Michigan together produce one-half of the total; following them come Indiana, Arkansas, Ohio, and Missouri. These six States report more than three-fourths of the total. Twenty mills in the North (Minnesota, Wisconsin, Michigan, Indiana) reported cuts of elm for 1917 in excess of 1 million feet; fifteen in the lower Mississippi valley reported similar cuts. From 15 to 20 million feet of elm veneer, not included in the lumber cut, is also produced each year, besides about 150 million feet of slack cooperage material. The annual production of cork elm lumber is about 13¼ million feet, of which 10 million feet is cut in Wisconsin, nearly all in Shawano, Langlade, and Forest Counties, and 3¼ million feet in Michigan. About half the elm cut in the three Wisconsin counties named is cork

elm. Elm lumber forms only a minor part of the total cut of the larger mills reporting, as few, if eny, of them make any special effort to get elm except as they happen upon it in the course of logging.

Practically all elm logs are plain sawed. From 18 to 20 per cent of the cork elm cut grades firsts and seconds, admitting widths as narrow as 4 inches, and from 24 to 30 per cent grades No. 1 common. The total amount of plain-sawed, straight grained, clear cork elm, suitable for propellers, that can be obtained from the present annual cut, it is estimated, will not exceed about 200 thousand board feet. This is only about 1½ per cent of the total cut. It is probable, however, that a much larger proportion, possibly from 15 to 20 per cent, will be suitable for other parts of aircraft. Because of the larger average size of the logs, an even greater part of the cut of white elm may be available for those uses to which this species is adapted, including the making of veneers. A comparatively small percentage of it will be of sufficient density to make longeron stock.

MARKETS AND USES FOR THE LUMBER.

At least 90 per cent of the elm lumber cut is further manufactured before it reaches the consumer. Twenty-six per cent goes into boxes and crates; 14 per cent into furniture (principally chairs, for which more elm is used than any other wood except maple and beech); 12½ per cent into vehicles; 6½ per cent into musical instruments; 5 per cent into refrigerators and kitchen cabinets; 3 per cent into agricultural implements; and 2½ per cent into trunks (especially slats). Smaller quantities are used for a great variety of products.

This wood is practically all used in the Northern and Eastern States, and the industries which take the largest amounts of elm are usually located fairly close to the sources of supply. A great deal of the cooperage material is manufactured into finished products in the South, near the places where it is cut.

A large part of the cork elm produced is used in vehicles, for hubs, bows, parts of the running gear, automobile bodies, logging-wheel spokes, sleigh runners, and carriage-wheel rims. Some is used for chair rockers, stepladders, ladder rungs, plow handles, scythe snaths, and many other articles.

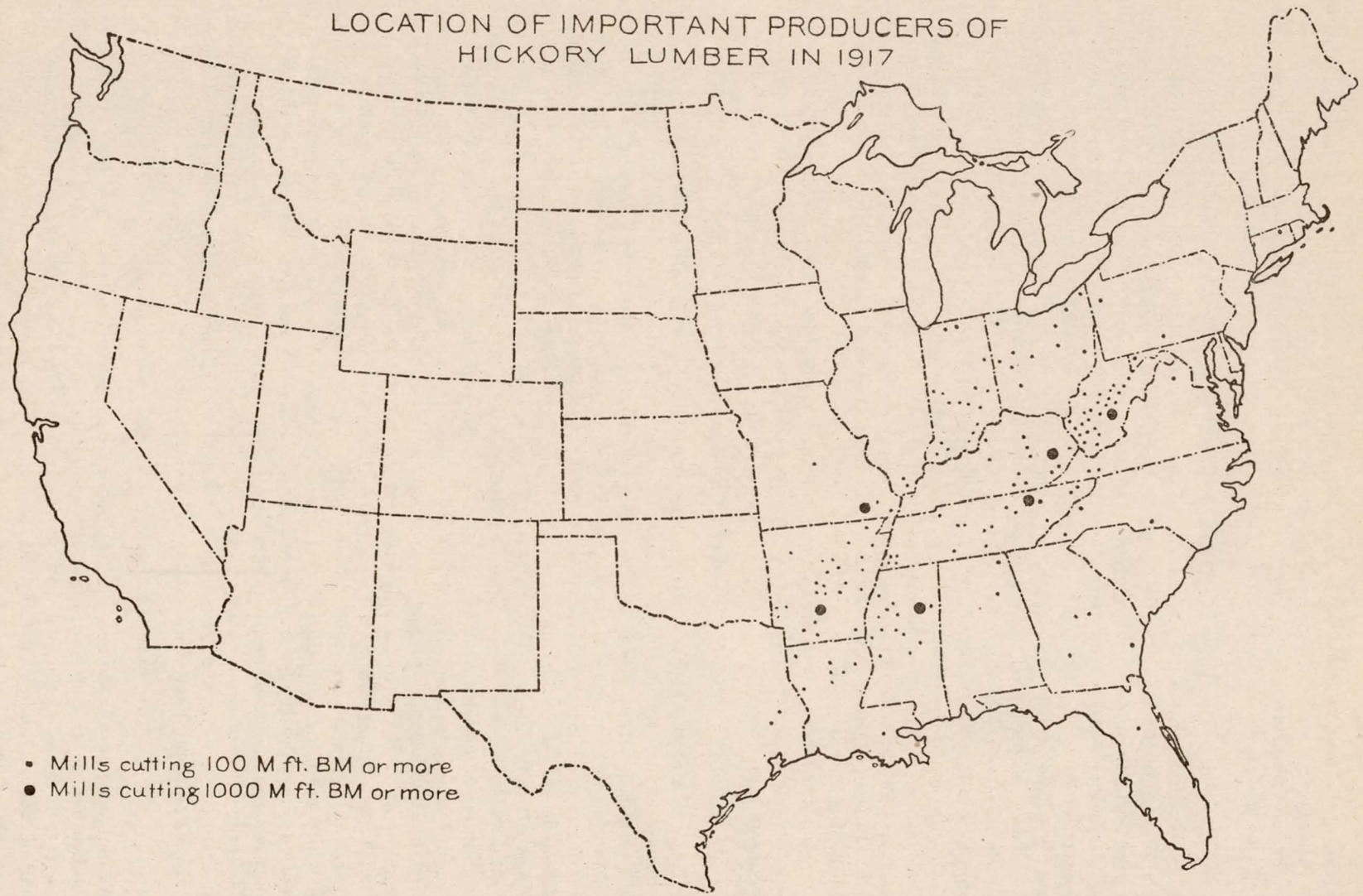
HICKORY.

SHAGBARK HICKORY (*Hicoria ovata*). SHELLBARK HICKORY (*Hicoria laciniosa*). PIGNUT HICKORY (*Hicoria glabra*). MOCKERNUT HICKORY (*Hicoria alba*). BITTERNUT HICKORY (*Hicoria minima*). WATER HICKORY (*Hicoria aquatica*). NUTMEG HICKORY (*Hicoria myristicaeformis*). PECAN HICKORY (*Hicoria pecan*).

There are several other hickory species of minor importance, but the greater part of the lumber cut is from the first five species.

DISTRIBUTION.

Shagbark hickory occurs from southern Maine through southern Quebec and Ontario to southern Minnesota and eastern Nebraska, and south to Delaware, and along the Appalachians to western Florida and Texas. It is most abundant on the western slopes of the southern Appalachians and in the lower Ohio Valley. Shellbark hickory is found from central New York to eastern Nebraska, and south to North Carolina and Oklahoma, and is most abundant in the bottom lands of central Missouri and the lower Ohio Basin. Pignut occurs from southern Maine to Nebraska and south to the Gulf of Mexico. It is most abundant in Missouri and Arkansas, and grows to largest size in the lower Ohio River Basin. Mockernut occurs from southern Ontario to Kansas and south to Florida and Texas, and is abundant in the lower Ohio Valley, Missouri, Arkansas, and the South Atlantic and Gulf costal regions. Bitternut covers about the same range as pignut, except that it is not found quite so far south. It is abundant in all of the Central and Northeastern States, and is the most common hickory of Iowa, Nebraska, Kansas, and southern New England. Water hickory grows in swamps of the coastal plain from southern Virginia to Texas and up the Mississippi Valley to southern Illinois. It is most abundant in Louisiana, Arkansas, and Mississippi. Nutmeg hickory is found from South Carolina to Mexico, and is most abundant in southern Arkansas. Pecan occurs in the Mississippi Valley from Iowa to Texas, east to southern Indiana and central Alabama, and west to eastern Kansas and Oklahoma.



MAP No. 17

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USE IN AIRCRAFT.

Wood of the first four species named above has been suggested as a possible substitute for ash in longerons, since it is tough and strong, though heavier than ash. So far as known, hickory has not been used for longerons. It is used to some extent for landing skids. The other species are less shock resistant and considerably inferior to these four.

SUPPLY OF TIMBER.

Hickory usually occurs scattered singly or in groups through mixed hardwood forests at low and medium elevations. Over limited areas it is frequently the predominant species. While it is fairly common throughout most of its range except in the higher mountains, it is most abundant and of best quality in the rich bottom lands of the Mississippi and Ohio Rivers and their tributaries. In this region, as well as in the southern Applachians, there are still large supplies of virgin timber. In the rest of the country most of the hickory is second growth, which, however, is considered to be fully as desirable as old-growth timber.

The total stand of hickory can only be guessed at. The best available estimate places it at about 16 billion board feet, of which 3 billion feet is in the central woodlot region, 2½ billion feet in the southern Appalachians, 2½ billion feet in the Atlantic and Gulf coastal region, and 7 billion feet in the lower Mississippi Valley region. The States with the largest supplies of hickory are, in about the following order: Arkansas, Missouri, Tennessee, Kentucky, North Carolina, Louisiana, Mississippi, Alabama, and West Virginia. These nine States have about two-thirds of the total stand.

The standing hickory is in the possession of a considerable number of large owners as well as of a multitude of smaller holders. It is a very common and widely scattered wood-lot tree, and occurs in large quantities on the holdings of lumber companies throughout the South.

PRODUCTION OF LUMBER.

A large part of the hickory used in the United States does not go through regular sawmills, but is cut directly into planks, squares, or billets, which are manufactured into spokes, handles, rims, and other products. For this reason the census figures on the production of hickory lumber do not give a sum anywhere near the total production of hickory used in the industries. During the years 1913 to 1917 the average cut of hickory lumber was about 120 million board feet, and this is less than half the average annual cut from 1907 to 1912, which was 254 million feet. The cut is steadily declining.

Arkansas, Tennessee, West Virginia, Mississippi, Kentucky, Indiana, and Ohio lead in the production of hickory lumber, and together produce nearly three-fourths of the total. Mississippi, Ohio, Louisiana, Missouri, and Pennsylvania are also important producing States.

Hickory from virgin forests such as are found in the southern Appalachians and in the lower Mississippi region, is cut in considerable quantities by large hardwood mills, which take it along with their other timber. The great bulk of the hickory production, however, comes from small or medium-sized mills. Many small operators specialize on hickory squares and billets, which are not recorded in lumber census reports. For the year 1917, only six mills reported cuts of more than a million board feet of hickory lumber, while about 150 reported cuts between 100 thousand and 1 million feet.

The proportion of the hickory cut that would be suitable for airplane work depends very largely upon the sizes in which it would be wanted. For short, narrow strips, such as are used for skids, a very large part of the cut would be suitable.

MARKETS AND USES FOR THE LUMBER.

Available figures on the amounts of hickory used about six years ago by various industries indicate a total consumption of 390 million board feet, which is 50 per cent, or 130 million feet, in excess of the average lumber cut for the five years previous to that time. The total cut of hickory lumber has fallen off to about 40 per cent of what it was then, but it is not known whether or not the total consumption of hickory has fallen off to the same extent.

Of the total of 390 million feet, 62 per cent was used by the vehicle industry, which took more hickory than any other wood, and, with the exception of oak, more hickory than all other woods combined. Handle manufacturers used 31 per cent of the total. Forty-three per cent of all wood used for handles was hickory. Agricultural implements took about 2½ per cent, athletic goods, 1½ per cent, and numerous other industries, small quantities.

Most of the hickory cut is used in the woodworking centers of the Central and Eastern States. In 1913 about 8 million feet of hickory in the log was exported, and this went chiefly to Canada, South Africa, Australia, and Germany.

SUGAR MAPLE.

(*Acer saccharum.*)

This species is also known as hard maple, rock maple, and black maple.

DISTRIBUTION.

The range of sugar maple extends from southern Newfoundland to Minnesota, and south to eastern Texas and northwestern Florida. It is of commercial importance chiefly in the Lake States, the Northeast, and along the Appalachian Range to northern Georgia. The best maple comes from Michigan, especially from the lower peninsula.

USE IN AIRCRAFT.

Sugar maple, being quite heavy, hard, stiff, resistant to wear, and of uniform texture, is a fairly satisfactory propeller wood, and has been so used where the requirements were not too exacting. Because of the same qualities it makes excellent face ply and finish. It has also been approved for bent work, skids, and engine bearers. Its comparative abundance, wide distribution, accessibility, and comparative cheapness promise for it an important future in airplane manufacture.

SUPPLY OF TIMBER.

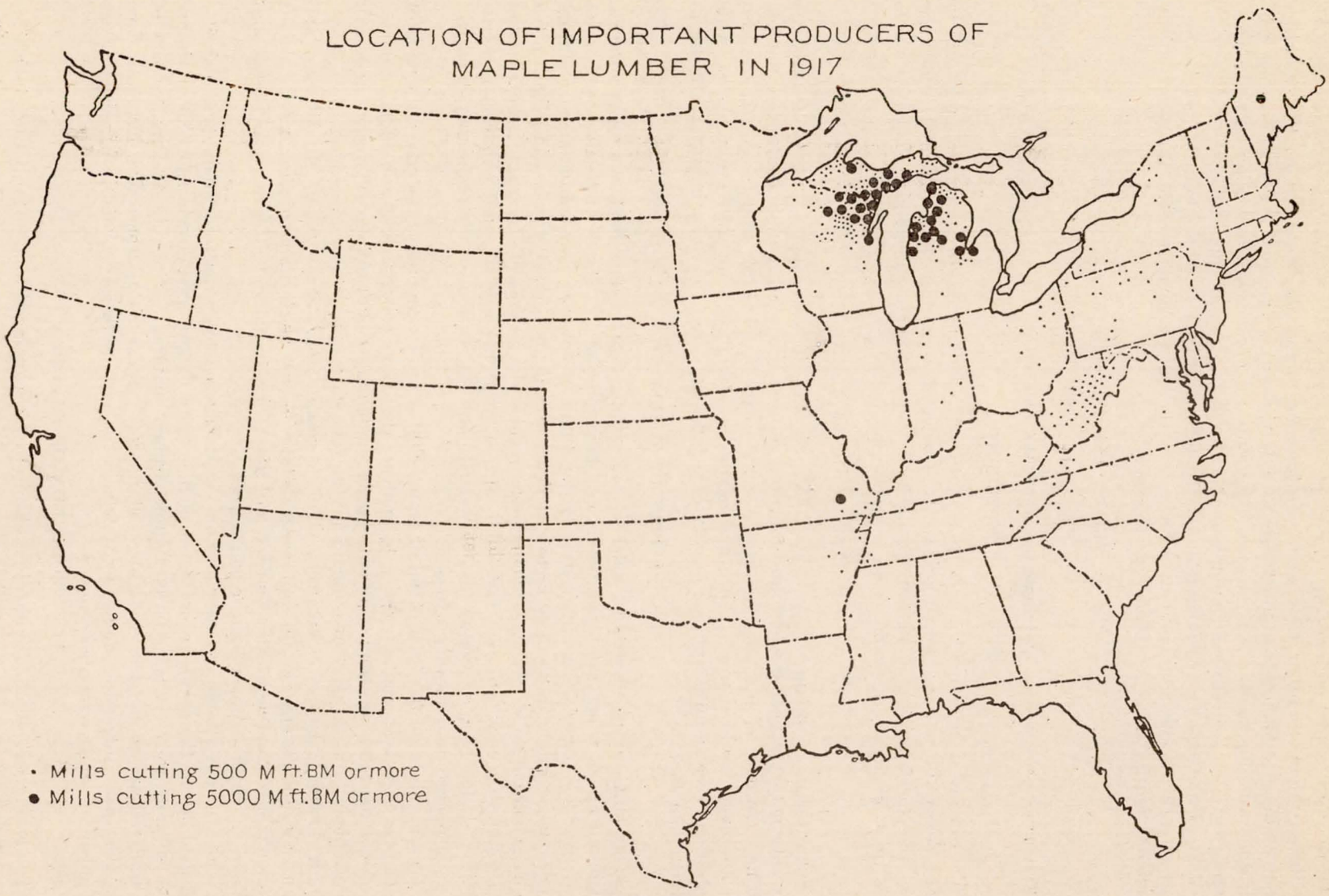
Sugar maple occurs scattered singly or in groups through mixed stands of hardwoods, most important of which are birch, beech, and basswood, and in stands of hemlock and white pine. It seldom forms a large proportion of the stand, except over very limited areas. Mature trees ordinarily run from 30 to 40 inches in diameter and from 100 to 120 feet in height, often with clear boles of 60 feet or more when grown in the forest. Most of the maple is so situated that it can be logged without any great difficulty, although much of it is not tributary to existing mills. It has been estimated that between 10 and 15 per cent of the remaining stand will be cut in operations now in progress.

Accurate data on the total stand of maple timber are lacking, as is the case with most of our species. The best available estimates indicate that there is between 40 and 50 billion board feet of merchantable size (including both sugar maple and the soft maples), of which one-fourth is in Michigan, and nearly three-fourths in the following nine States: Michigan, New York, Missouri, Maine, Wisconsin, Arkansas, Ohio, Vermont, and Pennsylvania. In Missouri and Arkansas soft maple is prevalent; in the other States named, sugar maple predominates. About 12 billion feet is standing in New England and New York, 15 billion feet in the Lake States, and 6 billion feet in the Appalachian region.

While there is a large quantity of maple in the aggregate on farmers' woodlots and similar small holdings in the maple region, most of it is more or less open-grown, short-boled timber which will not produce a large proportion of airplane material. Probably the greater part of such material will come from virgin forest stands such as exist in northern New England, New York, the Lake States, and along the Appalachians, and are largely owned in fair-sized blocks by lumber or land companies.

PRODUCTION OF LUMBER.

The annual cut of maple lumber in the United States averaged from 1913 to 1917, inclusive, about 900 million board feet, of which it is estimated about 80 per cent was sugar maple. The cut from 1907 to 1912 averaged a little less than a billion feet a year. While there is, therefore,


LOCATION OF IMPORTANT PRODUCERS OF
MAPLE LUMBER IN 1917
· Mills cutting 500 M ft. BM or more
● Mills cutting 5000 M ft. BM or more

MAP No. 18

a gradual decline in production, the rate is still quite well maintained. Forty per cent of the cut comes from Michigan and seven-tenths from the three States of Michigan, Wisconsin, and West Virginia. In Michigan and Wisconsin more than 95 per cent of the cut is made by large mills whose production is in excess of one million feet of maple each; in West Virginia about 80 per cent is cut by such mills. The larger concerns, as a rule, grade their lumber more carefully than the smaller ones and are better equipped to turn out well-manufactured, high-grade material in quantity.

Logging is carried on throughout the year in most operations, and horse logging is the rule, although a few of the larger operators use steam. Railroads are employed in many of the large enterprises.

The proportion of the cut which is suitable for use in aircraft depends, of course, upon the purpose for which it is wanted. It is estimated that about 3 per cent will be of the size and quality suitable for propellers if plain-sawed material is used, or 1 to 1½ per cent if quarter-sawed material is required. About 15 per cent of the entire cut, or of that part of it produced by larger mills at least, is in the two upper grades of firsts and seconds, while about 25 per cent is No. 1 Common. From 30 to 40 million feet of maple is normally cut into veneer.

MARKETS AND USES FOR THE LUMBER.

More than 90 per cent of the cut of maple lumber is further manufactured. Perhaps the most important use of high-grade sugar maple is for flooring. Of the total cut of all species of maple, 31.6 per cent is made into planing mill products, including flooring. In quantity, the maple manufactured by planing mills is exceeded among hardwoods only by oak. Of the maple lumber cut, 13.5 per cent is utilized for furniture and chairs, and the amount of it used for this purpose is exceeded only by oak. For boot and shoe findings, 5.4 per cent of the maple cut is used. This is 81 per cent of all the lumber taken by this industry and does not include the large amount of maple so used without being cut into lumber. In the making of agricultural implements 4.8 per cent of the maple cut is employed. Oak and yellow pine are the only woods used more extensively in this industry than maple. More maple than any other wood is utilized in making musical instruments, the percentage being 4.5 of the total cut. For the manufacture of handles, 4.1 per cent of the maple cut is taken, and only hickory and ash are used in larger amounts than maple in this industry. In the making of vehicles, and especially for the framework of trucks and automobiles, 3.6 per cent of the maple cut is employed. Two per cent of the maple cut is made into fixtures, and oak is the only wood used more largely than maple for this purpose. Large quantities are used for woodenware, laundry appliances, spools and bobbins, refrigerators, car construction, trunks, sporting goods (exceeded only by hickory), professional and scientific instruments (exceeded only by cedar used for pencils), and toys. The box and crate industry uses 9.6 per cent of the cut.

Maple flooring is sold all over the country. The maple used by the various industries is sold largely in the Central and Northeastern States where these industries are centered; consequently, very long railroad hauls are not ordinarily necessary.

OAKS.

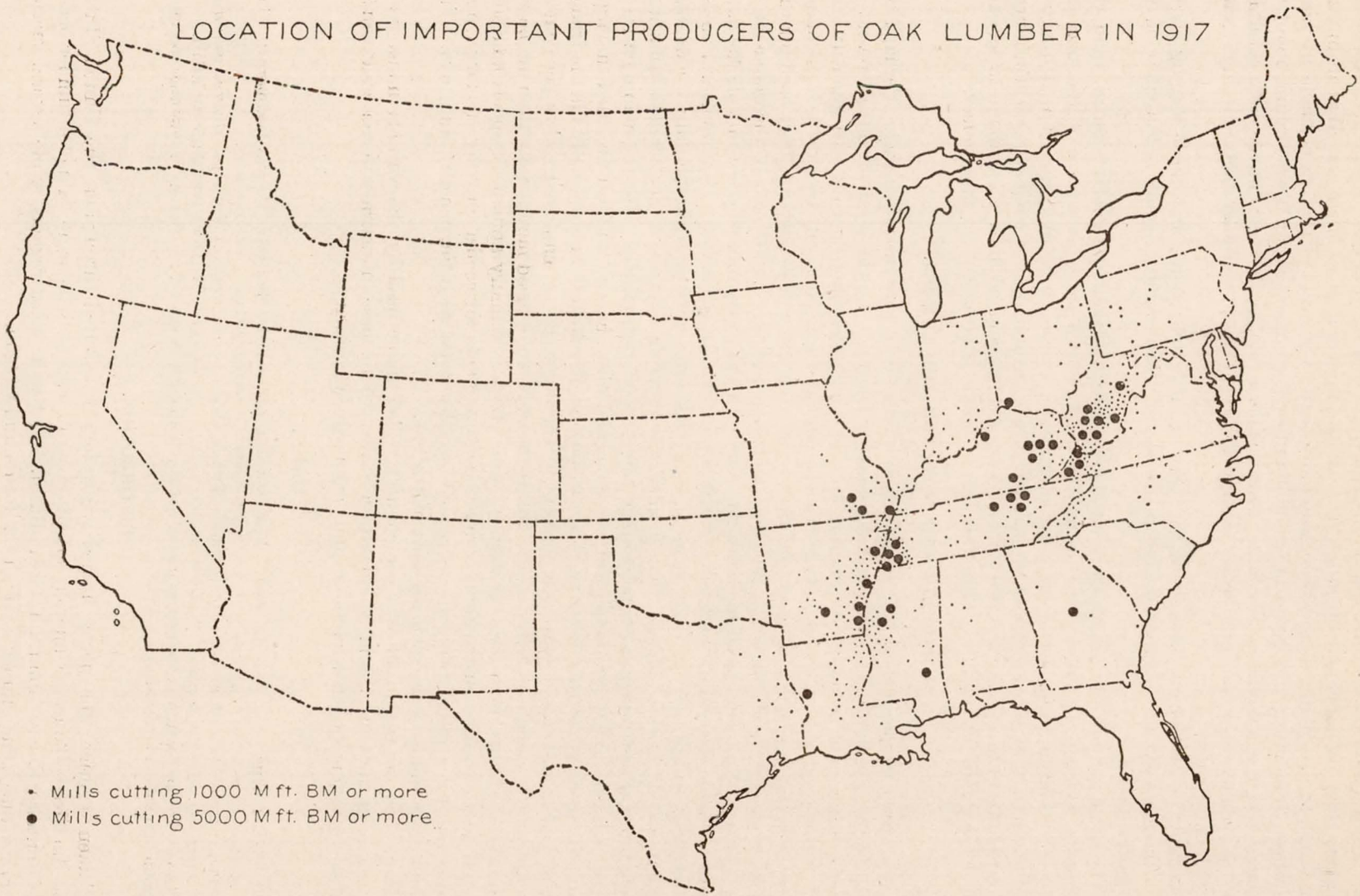
WHITE OAKS: White Oak (*Quercus alba*). Post Oak (*Quercus minor*). Bur Oak (*Quercus macrocarpa*). Cow Oak (*Quercus michauxii*). Overcup Oak (*Quercus lyrata*). Chestnut Oak (*Quercus prinus*).

RED OAKS: Red Oak (*Quercus rubra* or *borealis*). Texan Oak (*Quercus texana*). Pin Oak (*Quercus palustris*). Scarlet Oak (*Quercus coccinea*). Yellow (or Black) (*Quercus velutina*). Willow Oak (*Quercus phellos*).

These twelve species furnish the greater part of the oak lumber cut in the United States. A few other species in each group furnish small quantities.

DISTRIBUTION.

Taken together, the species named are widely distributed throughout the United States east of the Great Plains. Numerous species of scrub oaks of little or no value for lumber occur in the southern Rocky Mountain, Great Basin, and Pacific coast regions, while several species that do produce some lumber occur in California and Oregon.


LOCATION OF IMPORTANT PRODUCERS OF OAK LUMBER IN 1917
• Mills cutting 1000 M ft. BM or more
● Mills cutting 5000 M ft. BM or more

MAP No. 19

White oak occurs from southern Maine to southern Michigan, southern Minnesota, eastern Nebraska, and Kansas, and south to Texas and Florida. It is most abundant and of greatest commercial importance on the western slopes of the southern Appalachians and in the lower Ohio Valley bottomlands. Post oak occurs from southern Massachusetts to Florida and west to Missouri and Texas, and is of greatest commercial importance on dry uplands of the Mississippi basin. Bur oak occurs from Nova Scotia and New Brunswick to southern Manitoba and eastern Montana, and south to central New England, Pennsylvania, central Tennessee, and Texas. It is of greatest commercial importance in southern Indiana, Illinois, and Missouri. Cow oak occurs on bottomlands in the Coastal Plain and Mississippi Valley regions from Delaware to Texas and northward as far as southern Illinois and Indiana. It is of greatest commercial importance in the lower Mississippi Valley. The range of overcup oak extends from Maryland through southern Indiana to southern Missouri and south to Florida and Texas. It is most abundant in the lower Mississippi Valley and Gulf regions. Chestnut oak occurs in the Appalachian region from central New England to Alabama, and is most important commercially in the Carolinas and Tennessee.

Red oak ranges from Nova Scotia to north of Lake Huron, central Kansas, and along the mountains to Georgia. It is commercially important chiefly in the Northeastern States. Texan oak occurs in the Mississippi Valley from Iowa to Texas and up the Atlantic coast to North Carolina, and is of greatest commercial importance on the lower Mississippi bottomlands.

Pin oak occurs from southwestern New England to southern Missouri and southward to Virginia, Kentucky, and northern Arkansas, and is most abundant in the lower Ohio basin. Scarlet oak occurs from southern Maine to Nebraska, south to Illinois and the District of Columbia, and along the mountains to North Carolina. It is most abundant in the Atlantic coast region from Massachusetts to southern New Jersey. Yellow oak occurs from southern Maine to central Minnesota, and southward to northern Florida and eastern Texas. It is common throughout most of its range. Willow oak grows in bottomlands of the Coastal Plain region from Staten Island to Texas and up the Mississippi Valley to Missouri and Kentucky.

USE IN AIRCRAFT.

The white oaks shrink and swell with the weather less than do the red oaks. They glue well, finish well, and are very strong. The first four species named have long been approved as propeller woods. For propellers, quarter-sawed material is considered much superior to plain-sawed, because it shrinks less in a radial direction. There has been, so far, considerable prejudice against southern-grown white oaks. Whether this prejudice is justified is not yet fully known, but, with improved technique in the drying and working of lumber from these species it is probable that they may make satisfactory propeller woods.

The red oaks have not so far been used to any extent for propellers. It is possible, however, that selected, quartered red oak, at least of the northern species, may be found satisfactory. There is considerable variation in the strength properties of red oak lumber, even of one species. Moreover, red oak is more likely to be defective than white oak.

White oak of the four approved species has also been approved for structural and bent work on wings and fuselages.

SUPPLY OF TIMBER.

Oak occurs throughout most of its range on nearly all sites except the highest slopes and ridges. In the extreme northern part of the United States it does not make up an important proportion of the stand; but the proportion of oak increases to the southward, and from southern New England and the Central States to the Gulf the oaks are a very important part of the hardwood forests. In much of the region there is more oak than all other hardwood species combined. Thus the oak lumber cut in the States of Delaware, Maryland, Virginia, Illinois, Kentucky, Tennessee, Missouri, Oklahoma, and Texas exceeds the cut of all other hardwoods, while there is almost as much oak cut as all other hardwoods combined in New Jersey, Pennsylvania, North Carolina, Georgia, Alabama, West Virginia, Ohio, Indiana, and Arkansas.

Only very rough estimates of the stand of oak are available, and these do not distinguish the different species. It has been judged that about 47 per cent of the volume of all oaks belongs in the white oak group, and 53 per cent in the red oak group. White oak proper comprises nearly 22 per cent of the total, and the four species that have been approved for propellers constitute approximately one-third of the total stand of oak, which is estimated to be between 150 and 175 billion board feet.

About 40 per cent of the stand of oak is in the lower Mississippi Valley region, 25 per cent in the southern Appalachain region, and 15 per cent in the central woodlot region. Even in the Northeast and in the woodlot region, there are still some virgin stands of oak, which have been preserved for various reasons. Most of the old-growth oak, however, is now in the South.

PRODUCTION OF LUMBER.

During the period 1913 to 1917 the average annual cut of oak lumber of all species was approximately 3 billion board feet, which is 800 million feet less than the average cut during the preceding six years. The general tendency indicates a steady decline in the production of oak, as the virgin supplies become more nearly exhausted. Less than half as much oak lumber was produced in 1917 as in 1907. Besides the oak sawed into lumber, a great deal that is fit for lumber is sawed into ties, rived into staves, or used for veneer. From 30 to 50 million feet of white oak is made into veneer every year, while the white oak hewed into ties would produce from 500 to 1,000 million board feet of lumber. Nearly half of the oak lumber is produced in West Virginia, Tennessee, Arkansas, and Kentucky, and eight-tenths of the total comes from these States together with Virginia, Mississippi, Missouri, North Carolina, Pennsylvania, and Ohio.

More than half of the sawmills in the United States saw oak lumber. These include the very smallest mills as well as some of the largest. For the year 1917, 22 mills in the southern Appalachian region and 16 in the lower Mississippi Valley region reported cuts of more than 5 million feet of oak each, while some 330 reported cuts of between 1 and 5 million feet each. Most of these mills cut other species as well as oak; a few make oak a specialty.

Logging in most of the oak region is carried on during the greater part of the year, though more timber is cut in the fall and winter than during the spring and summer months. The small operators and many of the larger ones use animals for logging, and haul logs to their mills by wagon, truck, or rail. Many of the large concerns in the South log with steam, and most of them operate logging railroads. A few establishments, particularly in the farming sections, buy logs from farmers and contractors.

It has been estimated that at the present time about 58 per cent of the oak lumber cut is white oak. Of this about 27 per cent is cut into sawed ties and large timbers, and 20 per cent of the remainder grades firsts and seconds. To get quarter-sawed material 8 inches or more wide, such as is wanted for propellers, logs 23 inches or more in diameter are required. Approximately 15 per cent of the firsts and seconds cut by the larger mills will make quarter-sawed propeller material. About two-thirds of the white oak is cut by these larger mills, the very small mills not being equipped for quarter-sawing. On this basis, about 0.85 of 1 per cent of the total oak lumber cut will be suitable for propellers. Of course, the proportion of such material produced by different operators will vary widely. Mills that buy selected logs can cut a very much higher proportion than those that cut their own logs as they come to them.

MARKETS AND USES FOR THE LUMBER.

American oak lumber is sold all over the United States and in many foreign countries. During the fiscal year 1913, in round numbers, 3 million feet of oak logs and 300 million feet of oak lumber was exported from the country. By far the greater part of the oak used in the United States is sold in the territory east of the Mississippi and north of the Ohio and Potomac Rivers.

Nearly 40 per cent of it goes into ties, timbers, and rough lumber; 18 per cent into furniture; 16 per cent into planing mill products (flooring, interior finish, etc.); about 10 per cent (chiefly

low-grade material) into boxes and crates; 7 per cent into vehicles; 2 per cent each into agricultural implements, fixtures, and railway cars; 1 per cent each into shipbuilding and refrigerators; and smaller amounts into most of the other industries which use wood.

High-grade white oak of large sizes, which will yield propeller material, is cut largely into lumber for furniture, railway cars, and shipbuilding, or into veneers. A considerable quantity, particularly in the South, is rived into staves for tight cooperage.

YELLOW POPLAR.

(*Liriodendron tulipifera.*)

This species is also known as tulip poplar, tulip tree, white wood, and hickory poplar. Cucumber (*Magnolia acuminata*) and evergreen magnolia (*M. foetida*), which are usually cut and sold with poplar and have about the same strength properties, are included with it in the following discussion.

DISTRIBUTION.

Yellow poplar occurs in all States east of the Mississippi River except Maine, New Hampshire, Vermont, and Wisconsin, and occurs also in Missouri, Arkansas, and Louisiana. Cucumber does not occur quite so far to the northeast and to the south as poplar. Evergreen magnolia is found principally in the southern Atlantic and Gulf coast regions. Virgin stands of poplar containing large-sized timber are now to a considerable extent confined to the Appalachian region southward from Pennsylvania, and to bottomlands of Tennessee, Georgia, and Alabama.

USE IN AIRCRAFT.

Yellow poplar has been used with satisfactory results for most of the wooden parts of aircraft. While a little heavier than spruce and inferior to it in shock resistance, it is comparatively strong, free from checks and shake, retains its shape well, and is easy to work. It is a fairly satisfactory substitute for spruce in making wing beams and struts, as well as for wing ribs, and has been used to some extent for propellers, particularly by the French. It makes excellent cores for plywood and has been so utilized in considerable quantities.

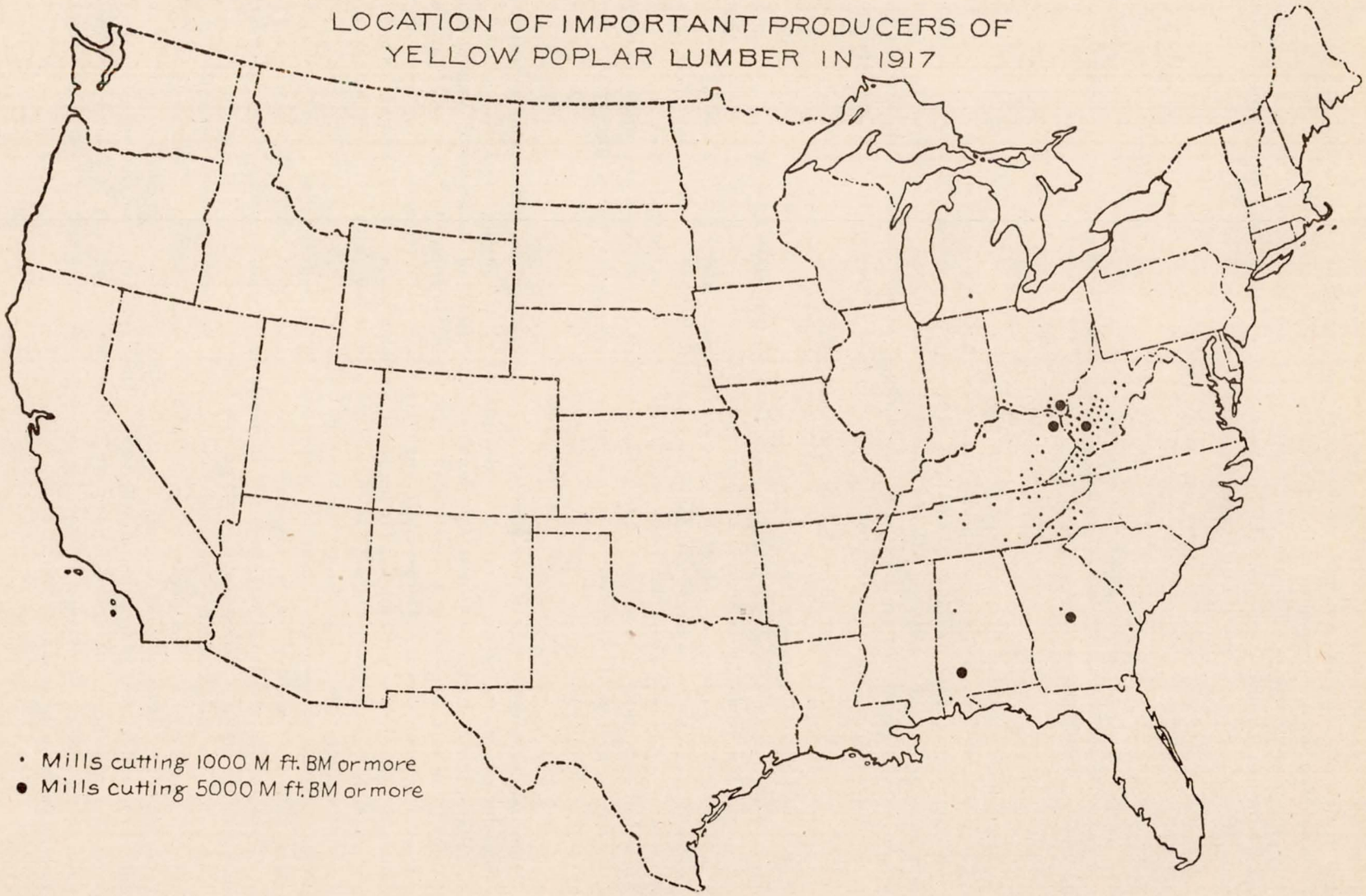
Its wide distribution, its accessibility, its occurrence within easy reach of centers of aircraft manufacture, as well as its excellent qualities, make yellow poplar a very important species for aircraft construction.

SUPPLY OF TIMBER.

Yellow poplar never occurs in pure stands over considerable areas, but appears as scattered individuals or groups in forests of mixed hardwoods, or of hardwoods and hemlock, pine, or occasionally spruce. In the southern Appalachians, the region of its greatest abundance, it constitutes from 10 to 30 per cent of the stand in virgin timber, or from 1 to 3 thousand board feet per acre over extensive areas. Occasionally single acres have been reported having as much as 75,000 board feet. In the bottomlands farther south a smaller proportion of the stand is poplar. In virgin stands trees average from 30 to 36 inches in diameter, with 50 to 60 feet clear of branches; diameters of 6 feet are by no means rare.

Poplar is a tree of the lower and middle slopes and coves, and, therefore, to a considerable extent is in fairly accessible places. However, part of the region where it grows is not yet provided with road or railroad facilities, and it is estimated that not more than half of the remaining virgin stand is accessible to existing sawmills.

The total amount of standing poplar is not known. Rough estimates place it at about $9\frac{3}{4}$ billion board feet, of which perhaps 7 billion feet is virgin timber. Three-fourths of the total stand is in the States of West Virginia, North Carolina, Tennessee, Kentucky, and Virginia. All but a few million feet is in private ownership. The greater part of the remaining virgin timber is in fairly large holdings of lumber companies, coal companies, and land investment companies. Second-growth stands are held by the large companies and by many small owners in different parts of the poplar region.


LOCATION OF IMPORTANT PRODUCERS OF
YELLOW POPLAR LUMBER IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 5000 M ft. BM or more

MAP No. 20

PRODUCTION OF LUMBER.

The annual cut of yellow poplar lumber from 1913 to 1917 averaged 480 million board feet, and is steadily declining. About one-half as much is now cut each year as was produced ten years ago. West Virginia now produces one-fourth of the total, and is followed by Tennessee, Kentucky, Georgia, Virginia, North Carolina, and Alabama, in the order named. These States produce more than 90 per cent of the total cut.

About one-half of the total is cut by large, well-equipped mills of which there are approximately 75 cutting more than one million feet of poplar each. Another one-fourth of the total is cut by some 350 medium-sized or large mills, each of which cuts in excess of 100,000 board feet of poplar. Small mills cut the rest, mostly from second-growth stands which produce very little high-grade lumber. Except for a few which buy logs and specialize on poplar, all of these mills cut a variety of species, and take poplar only as it comes in the stand. Of the lumber cut by the 75 largest producers, 18 per cent was poplar, and by the smaller producers, about 7 per cent. On the basis of their rated capacity and these proportions of poplar, large mills are capable of producing 275 million feet of poplar, while the medium-sized mills could produce 150 million feet. The smaller mills, which now cut less than 100 thousand feet of poplar each, could probably produce 100 million feet a year if operated to their full capacity.

At the present rate of cutting, the existing larger mills have sufficient standing poplar to last them, on the average, from 10 to 12 years. It seems probable that, after the next 15 to 20 years, almost the entire cut will come from small mills and largely from second-growth stands.

Logging is now done with steam quite generally in the southern part of the poplar region, while horses are commonly used in West Virginia. Practically all of the large operations employ railroads. A few operators use motor trucks to some extent to bring in logs, and several large companies along the Ohio River, depend upon water transportation. Operations are carried on throughout the year, although it is customary to try to log the greater part of the poplar in fall and winter, on account of the tendency of logs to sapstain when they are cut during the summer. Logs are seldom cut more than 16 feet in length, though longer ones can be gotten out by the larger operators when such material is wanted.

Under normal conditions no particular effort is made to saw straight-grained material, but the larger producers use considerable care to saw lumber of the upper grades. Poplar is characteristically straight grained, with little taper, so that probably 75 per cent of the clear lumber produced has grain straight enough to make it suitable for aircraft use.

Most of the airplane material will probably come from the upper grades, including panel, wide No. 1, firsts and seconds, and saps and selects. The proportion of this material that is produced varies widely with different stands and regions. The average figure for the large mills is about 26 per cent, and it is estimated that perhaps 75 per cent of this amount will be suitable for airplanes. Probably not more than 5 or 6 per cent of the material from second-growth stands will meet present airplane standards. It is judged that approximately 60 million board feet of the present cut of 350 million feet will fulfill the requirements for airplane work if it is sawed to the desired sizes.

In addition to the above lumber cut, from 25 to 35 million feet of yellow poplar, chiefly high-grade material, is ordinarily cut into veneer each year. Much of this is suitable for airplane plywood.

MARKETS AND USES FOR THE LUMBER.

Practically the entire cut of yellow poplar is further manufactured, and it is used by a very great variety of industries. Thirty-three per cent of the cut is made into sash, doors, finish, siding, and other planing mill products. For furniture, including chairs, 7½ per cent is used. Seven per cent goes into vehicles, and only hickory and oak are used in larger quantities by this industry. Six per cent is employed in making musical instruments. In this industry, maple is the only wood more largely used than poplar. For car construction, 4½ per cent of the poplar cut is taken, and oak is the only hardwood more extensively employed. In manufacturing bungs and faucets, 2½ per cent of the poplar is utilized—86 per cent of all the wood used by this

industry. Two per cent is made into fixtures, and the same amount into agricultural implements. A large number of industries use smaller quantities. Box and crate manufacturers take 23 per cent of the cut, mostly low grade material.

Yellow poplar is sold in large quantities in the Central and Northeastern States, where most of the wood-using industries are located. Considerable quantities are normally exported to the countries of western Europe, in whose markets American yellow poplar is a standard wood.

BLACK WALNUT.

(*Juglans nigra.*)

DISTRIBUTION.

Black walnut occurs from southern New England to southern Ontario, southern Minnesota, and south to eastern Texas and Florida. It reaches its best development and is found in largest quantities in the central woodlot region centering in Ohio, Indiana, Illinois, eastern Iowa, Missouri, Kentucky, Tennessee, and West Virginia. It has also been planted to some extent beyond its natural range. The small quantities, limited distribution, and habits of growth of the other black walnut species, the Mexican and California walnuts, render them of no importance as a source of airplane material.

USE IN AIRCRAFT.

Black walnut makes the best propellers of any native species. It is easy to work, finishes well, is very resistant to wear and to shocks, and retains its place remarkably well. It also makes excellent facing plywood, both flat and bent.

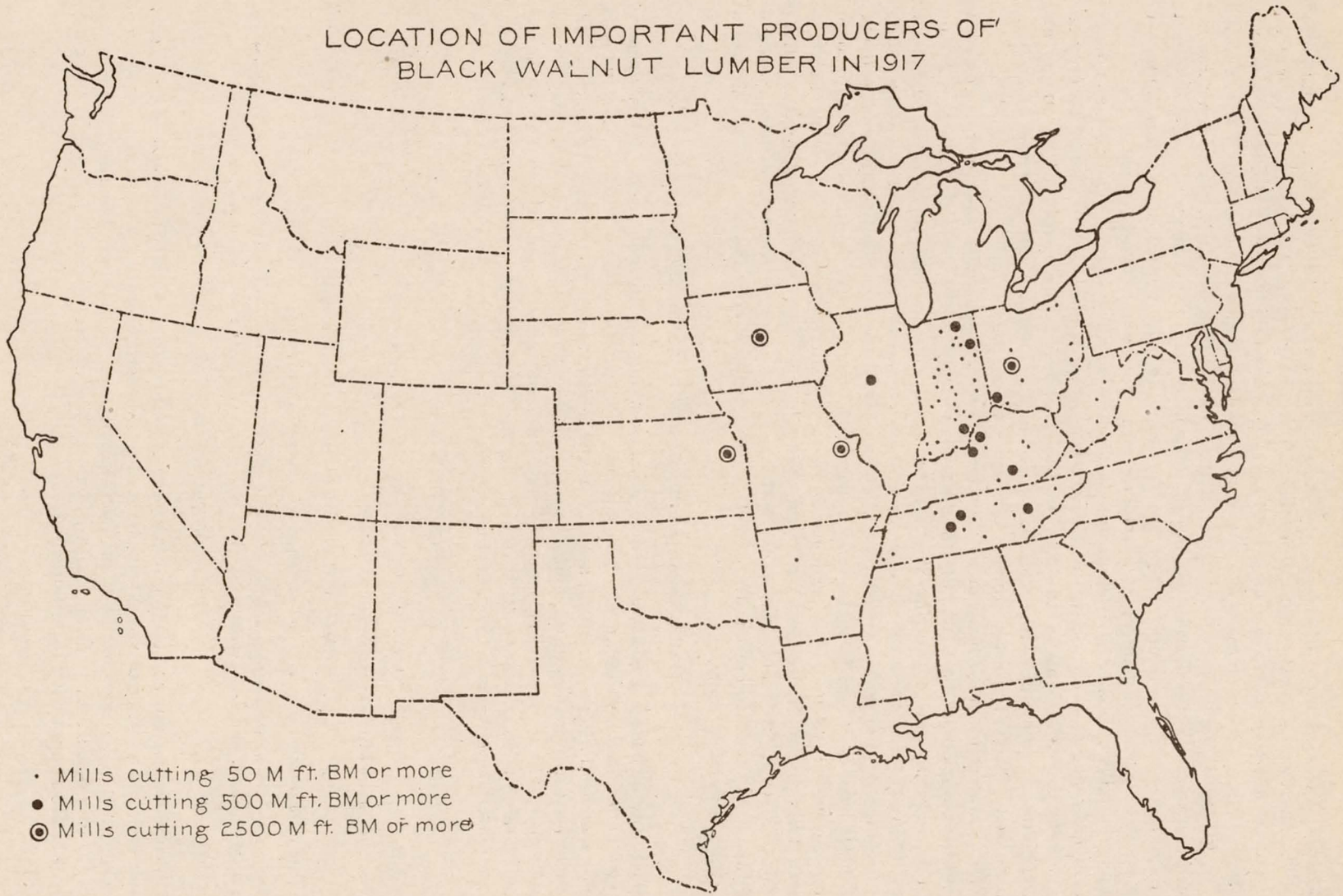
While, on account of the scarcity of the remaining high-grade walnut and its consequent high price, other woods may in the future come to be used much more for propellers, it is likely that walnut will always be an important wood for this purpose.

SUPPLY OF TIMBER.

Walnut has been in demand for many years for furniture, veneers, cabinet work, and gunstocks, and the once large supply was already greatly reduced prior to 1914. Since that year, and particularly since 1917, the enormous demand for walnut for war uses has made serious inroads on the remaining accessible supply.

It occurs scattered singly through stands of mixed hardwoods, and is a very common field or roadside tree in the region of its best development. The cut in recent years has probably come largely from trees grown in the open or in groves. The best trees are found in fairly rich agricultural soil, where they grow somewhat rapidly and reach large size. The average trees that remain in the more Northern States are somewhat smaller than those in the States farther south, but are of better quality. Eighty per cent of the logs now cut run between 12 and 20 inches in diameter at the small end. The open-grown walnut timber is, of course, practically all accessible, but a large part of that grown in the forest is some distance back from roads and not easy to get at.

Estimates of the existing stand of walnut are very unsatisfactory and differ widely. The best available figures, which probably do not allow for the greatly stimulated cut during the past two or three years, indicate a stand of about 850 million board feet. The eight States, Missouri, Illinois, Tennessee, Kentucky, Ohio, Arkansas, and Indiana, have about 70 per cent of the total stand. The entire amount is distributed about as follows: Central woodlot region, 550 million feet; southern Appalachian region, 200 million feet; Gulf and Atlantic States, 100 million feet. This estimate includes all trees over 8 inches in diameter; therefore, the stand of timber, about 16 inches in diameter and upward, that will produce airplane material, must be very much smaller. By far the greater part of the standing walnut is widely scattered and is in the hands of small holders, most of whom are farmers rather than timberland owners.


LOCATION OF IMPORTANT PRODUCERS OF
BLACK WALNUT LUMBER IN 1917
· Mills cutting 50 M ft. BM or more
● Mills cutting 500 M ft. BM or more
◉ Mills cutting 2500 M ft. BM or more

MAP No. 21

PRODUCTION OF LUMBER.

Because of the scattered distribution of walnut and its production by a large number of small mills, figures on the annual cut of lumber are probably far from complete. The average annual cut during several years prior to 1914 was about 40 million feet, besides considerable quantities cut into veneer or exported in the log. Some 13 million feet of logs were exported in 1913. After 1914, from 75 to 90 million feet a year was cut and by 1918 a much larger amount had been reached. It is probable that the production of walnut lumber will soon fall back to the prewar figure or considerably below it. Indeed, this must happen unless the supply of timber is much larger than the most optimistic estimates have allowed.

Some 200 mills normally cut walnut lumber along with other woods. Only about a dozen mills ordinarily specialize on walnut to the exclusion of other species, and these probably cut nearly half of the total. Walnut mills draw on wide sections of country for their log supply, and have to maintain considerable forces of buyers to locate, purchase, and assemble the logs at shipping points. Logs are often shipped 300 miles to the mill.

Walnut lumber intended for ordinary commercial uses is generally plain sawed in order to bring out the grain, and no particular attempt is made to saw straight-grained material. All important producers are now entirely familiar with sawing airplane material, and may be expected to continue to saw it if there is a sufficient demand for such material at prices that will attract them.

It is estimated that on the average about 18 per cent of the log scale is suitable for propeller stock, considering only logs 12 inches and upward in diameter. At certain mills the proportion runs considerably higher. In some instances this is due to greater care being exercised in selecting logs for purchase, and in others to the better average quality of the walnut that is grown in the North. It seems likely that with the return of normal conditions the quality of logs obtained will tend to deteriorate, or else the cut will fall very much below the figures at which it stood in recent years.

MARKETS AND USES FOR THE LUMBER.

Black walnut has long been valued for cabinet-making and for gunstocks. It is normally employed in large quantities in the manufacture of sewing machines, musical instruments, furniture, interior finish and fixtures, and for many lesser uses. It is widely utilized in the wood-manufacturing centers of the United States, and for many years previous to the war was exported, mostly in the log. The greater part of walnut exports formerly went to Germany, and considerable quantities to Great Britain. During the war large quantities of propeller and gunstock material were sent to the allied countries, particularly France and Great Britain.

COTTONWOOD.

COMMON COTTONWOOD (*Populus deltoides*).

This species is also known as big cottonwood, yellow cottonwood, and Carolina poplar.

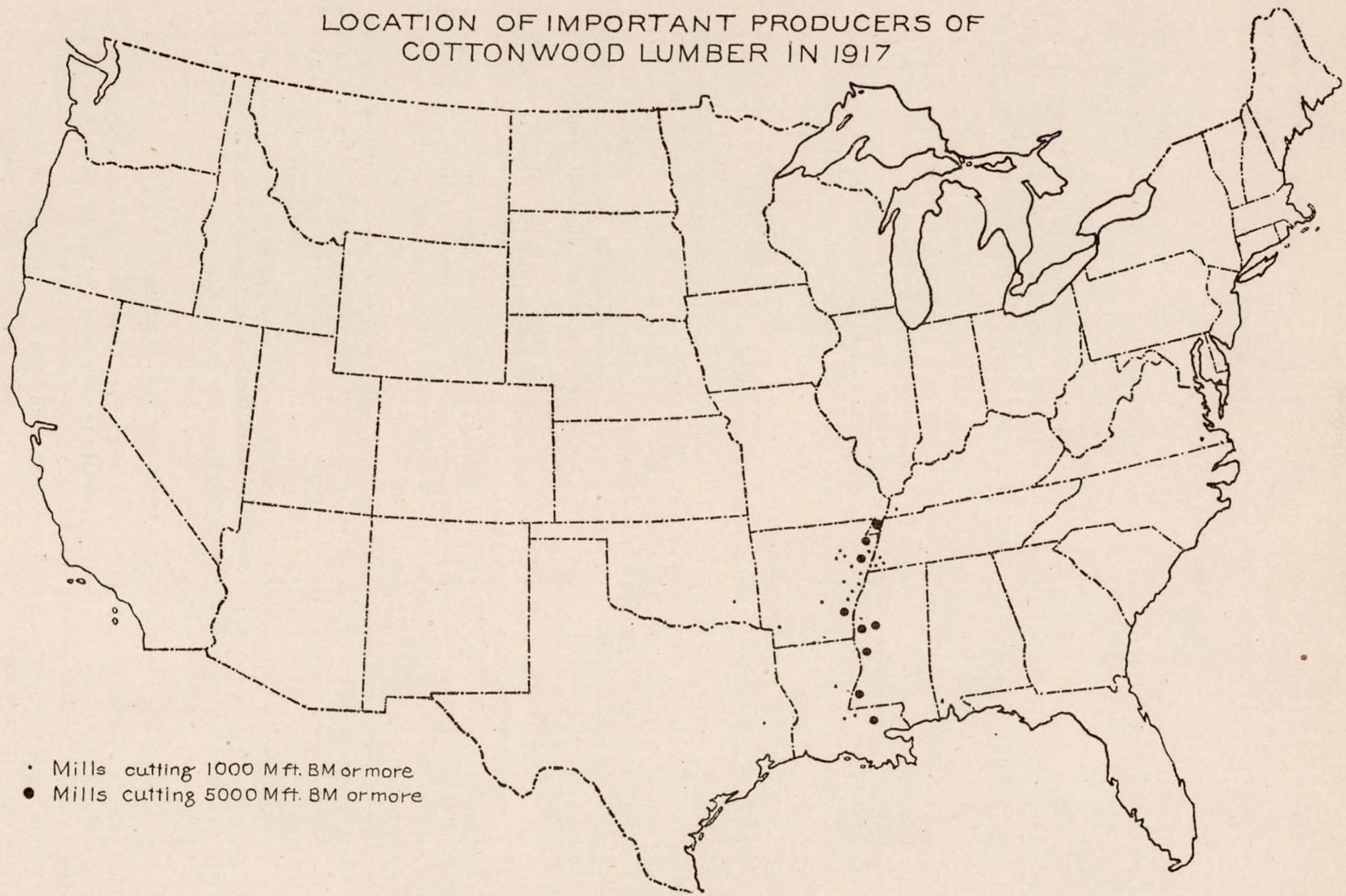
SWAMP COTTONWOOD (*Populus heterophylla*).

This species is also known as black cottonwood, river cottonwood, and swamp poplar.

These two species are the most abundant and furnish the bulk of the cut. Small amounts of various species, including Balm of Gilead, narrow-leaf cottonwood, black cottonwood (western), aspen, and others, are also cut.

DISTRIBUTION.

The common cottonwood occurs over practically the entire United States east of the Rocky Mountains, except in the extreme Northeast and in southern Florida. The swamp cottonwood is largely confined to the Coastal Plain from Connecticut to western Louisiana, and up the Mississippi valley to southern Illinois and Indiana. The optimum region for both is the valley of the lower Mississippi with its tributary streams.


LOCATION OF IMPORTANT PRODUCERS OF
COTTONWOOD LUMBER IN 1917
· Mills cutting 1000 M ft. BM or more
● Mills cutting 5000 M ft. BM or more

MAP No. 22

USE IN AIRCRAFT.

Cottonwood is low in its strength properties, but is light, tough, and fairly easy to work. Furthermore, it is cheap, fairly abundant, and accessible. It has been employed to some extent for plywood cores, in aircraft construction, and its use for this purpose may be considerably extended.

SUPPLY OF TIMBER.

The greater portion of the cottonwood lumber cut is from the common cottonwood. It is found principally along streams and often in pure stands or mixed with willows over small areas. Such stands are usually very open. Much of the mature cottonwood is associated with ash, soft maple, sycamore, red gum, tupelo, cypress, oaks, and other hardwoods, in mixed stands. In the lower Mississippi valley the trees reach large size, with diameters of from 4 to 6 feet and heights between 125 and 175 feet. Growth is extremely rapid and yields per acre are relatively large. The swamp cottonwood grows in similar situations and is cut along with the common cottonwood.

The available estimates of the stand of cottonwood are very rough and unsatisfactory. It has been judged that there is approximately 10 billion board feet in trees above 8 inches in diameter. Two-thirds of it is in Arkansas, Louisiana, Missouri, Mississippi, and Oklahoma. More than three-fourths is in the lower Mississippi valley region, a little more than a billion feet in the Coastal Plain region, and possibly three-fourths billion feet in the Great Lakes region. Most of the extensive stands of the Mississippi region are owned by large lumber companies. The cottonwood in Kansas, Iowa, Minnesota, Illinois, and Indiana is mostly in planted groves and owned in small units by farmers and others.

PRODUCTION OF LUMBER.

The average annual cut of cottonwood lumber in the United States between 1913 and 1917 was 195 million board feet, which is nearly 50 million feet less than the average cut during the preceding six years. In addition, large amounts of cottonwood are cut into veneer, excelsior, and pulpwood. The cut is gradually decreasing, which indicates that the supply of standing timber is probably becoming limited. Considering the rapid growth of cottonwood, however, it would seem that the present rate of cutting might be maintained almost indefinitely if the forests are carefully handled.

The most important cottonwood-producing State is Mississippi, which cuts more than one-fourth of the total. A close second is Arkansas, followed by Louisiana, Minnesota, and Missouri. These five States cut about three-fourths of the total. The cut in Minnesota is chiefly aspen and Balm of Gilead, and no mill in that State reports a cut in excess of a million board feet of cottonwood. In the South, 27 mills reported for 1917 cuts of between 1 and 5 million feet, and 9 mills reported cuts in excess of 5 million feet.

Cottonwood, together with associated species, is logged to stream banks, usually by animals, and from there it is usually towed on barges or in rafts to the mills, which are often many miles distant. Logging operations proceed throughout the year, except as they may be interfered with by floods. The lumber that might be used for aircraft will come largely from material graded as wagon-box boards and firsts and seconds. The proportion of these grades in the lumber cut varies from about 25 per cent in comparatively young stands to 40 or 50 per cent in old stands of large timber. These figures apply to the lower Mississippi valley cottonwood only; the proportion is probably smaller in the stands farther to the north.

MARKETS AND USES FOR THE LUMBER.

Practically the entire cut of cottonwood lumber is further manufactured. Cottonwood is in great demand for boxes and crates, and nearly two-thirds of the lumber cut is used by this industry. The vehicle industry uses about 10 per cent of the cut, chiefly for wagon-box boards, which requre high-grade material. Slightly more than 6 per cent goes into planing-mill products, 5 per cent into agricultural implements, 4 per cent into woodenware, nearly 3 per cent

into laundry appliances, about 2 per cent into furniture. Refrigerators, trunks, railroad cars, musical instruments, and fixtures take considerable quantities. Cottonwood veneer in the form of plywood is widely used for furniture, musical instruments, and similar uses. A great deal of cottonwood not reported in the lumber cut figures goes into excelsior, and a large amount is made into pulp for paper manufacture.

Cottonwood is used throughout most of the United States, and considerable quantities of plywood made from it were shipped to Europe before the war.

RED GUM.

(*Liquidambar styraciflua.*)

This species is also known as satin walnut, sweet gum, and liquidambar.

DISTRIBUTION.

Red gum occurs from southern Connecticut to southeastern Missouri and south to Texas and Florida. It reaches its best development and is most abundant in the lower Mississippi valley, from the mouth of the Ohio River southward.

USE IN AIRCRAFT.

Red gum is an excellent material for the manufacture of plywood, and is so used to a very great extent for commercial purposes. Its use has been approved for airplane plywood. The large and fairly accessible supply of this species makes it a promising wood for future use in the aircraft industry.

SUPPLY OF TIMBER.

Such incomplete estimates as are available indicate a total stand of red gum of approximately 44 billion board feet; of this amount 30 billion feet is in the Mississippi Valley, including tributary streams, and 14 billion feet is in the Atlantic and Gulf Coastal Plain region. The States having the largest supplies are, in the order named: Mississippi, Arkansas, Louisiana, Texas, Alabama, Georgia, South Carolina, and North Carolina. These States together have about 80 per cent of the total.

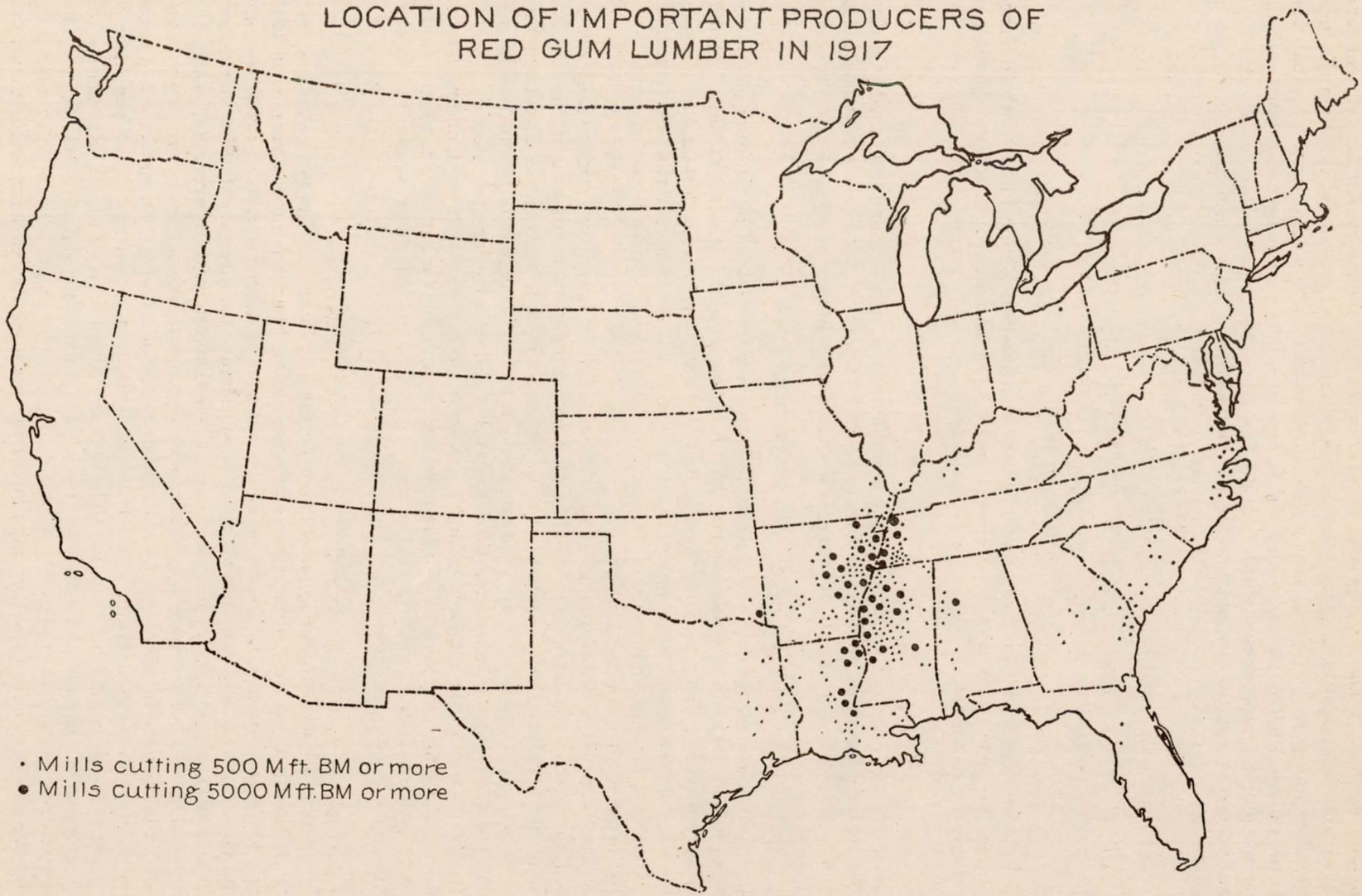
Although limited areas of young stands are occasionally found, red gum usually occurs scattered through mixed hardwood stands. It grows chiefly on bottom lands more or less subject to overflow during part of the year. Its associates include such species as cottonwood, soft maple, ash, tupelo, oaks, pecan, cypress, and sycamore. The gum is frequently the predominant species. Mature trees often reach diameters of 4 or 5 feet or even more.

The greater part of the remaining stand of mature gum is owned by large land and lumber companies. Since the gum land will for the most part be suitable for agriculture when drained, it seems probable that the supply of timber when once removed will never be renewed in anything like the original quantity.

PRODUCTION OF LUMBER.

The average annual cut of red gum lumber between 1913 and 1917 was 740 million feet, or about 100 million feet more than the average cut during the preceding six years. In 1917 it was about 790 million feet. Production of this species will probably not fall below the present figure for several years. The figures given do not include the large amounts cut for veneer. In 1910 and 1911, the last years for which reports on that product are available, nearly 150 million feet, log scale, of red gum was cut into veneer, practically all by the rotary process. About 35 mills reported for 1917 cuts of red gum in excess of 5 million feet each. All of these are in the lower Mississippi region. About 200 mills in this region and 35 in the Atlantic coast region reported cuts of between 500 thousand and 5 million board feet. Arkansas leads in the production of red gum, and is followed by Mississippi and Louisiana. These three States cut about two-thirds of the total.

Logs are generally cut in the fall and allowed to season somewhat before being towed out on rafts or barges. A few operators in drier territory have railroads and use steam in logging.


LOCATION OF IMPORTANT PRODUCERS OF
RED GUM LUMBER IN 1917
· Mills cutting 500 M ft. BM or more
• Mills cutting 5000 M ft. BM or more

MAP No. 23

Usually only the larger trees are cut, since small trees contain a large proportion of sapwood, which brings comparatively low prices.

It is estimated that from 20 to 25 per cent of the cut in the Mississippi region is firsts and seconds clear heart, while in the coast region not more than from 5 to 8 per cent is of this grade. Clear sap runs about 25 per cent in the valley States and 32 per cent on the coast. Material suitable for aircraft veneer would probably correspond to these two grades.

MARKETS AND USES FOR THE LUMBER.

A very large proportion of the clear heart gum used to be exported to the countries of western Europe and around the Mediterranean, where it is in great favor for furniture and finish. Practically all of the rest is used in industries in this country, almost none being consumed as rough lumber.

Approximately half of the lumber and veneer used in this country is made into boxes and crates. The quantity of red gum used by this industry is surpassed only by that of white and yellow pines. Fifteen per cent is used for planing-mill products, chiefly finish. Thirteen per cent goes into furniture, 3 per cent into vehicles (wagon boxes), 2½ per cent into sewing machines, and smaller quantities into a great variety of industries.

MAHOGANY.

CENTRAL AMERICAN MAHOGANY (*Swietenia mahagoni* and *S. macrophylla*).

AFRICAN MAHOGANY (*Khaya senegalensis*).

Numerous other species of Khaya, Entandrophragma, Trichilia, and other genera are also sold as African mahogany

PHILIPPINE MAHOGANY (*Shorea polysperma*).

This species is also sold under the name of Tanguile or Bataan mahogany. Red Lauan (*S. negrosensis*) is sometimes called Philippine mahogany.

DISTRIBUTION.

True mahogany (the American species) occurs from southern Florida to Colombia, Venezuela, and British Guiana. It is most abundant in southern Mexico (Vera Cruz, Tabasco, Campeche, and Chiapas districts), in Central America, and in the larger islands of the West Indies.

African mahogany is found in the forest belt of the west coast of Africa from the Senegal River to the southern boundary of Angola, and across central Africa to German East Africa and Madagascar. The largest supplies are in a belt varying in width from a few miles up to 200 miles, from the Senegal River to the Niger, and in a narrower strip from southern Nigeria to the northern part of French Congo. The best species, *Khaya senegalensis*, is nearly all between the Senegal and the Niger, although it is scattered to some extent in the forests of East Africa.

The so-called Philippine mahoganies occur in the Philippines and in neighboring parts of Malaysia.

USE IN AIRCRAFT.

The true mahogany is a most excellent propeller wood, and has been very extensively used for that purpose. Selected pieces of African mahogany are as satisfactory as the true mahogany, but on account of the wide variation in strength properties between the different species and between different lots of lumber from the same species, together with the difficulties in distinguishing the different species by inspection, African mahogany has not been popular as a propeller wood. The Bataan mahogany from the Philippines has also found a limited use for propellers.

Both the American and the African mahoganies make excellent plywood, but will hardly be used for that purpose on a large scale because of their high cost as compared with native woods which are quite as satisfactory.

SUPPLY OF TIMBER.

Mahogany occurs as a scattered tree in dense tropical forests, which are composed of a very large number of species. This is equally true of the Central American and the African species. The supplies of standing timber are very little known except in the regions which have been worked for years.

The total stand of true mahogany in Central America and Mexico has been roughly estimated at 19 billion 450 million board feet, and that in Cuba at 750 million board feet. Of this, about one-third is available to present operations; the rest can be reached only by the construction of railroads or by the introduction of different methods of logging. Mexico has 15 billion feet, Honduras 1¾ billion feet, Nicaragua 1½ billion feet, Guatemala three-fourths of a billion feet, Costa Rica one-fourth of a billion feet, and Panama and British Honduras 100 million feet each. Information is not available regarding the supplies in the West Indies, with the exception of Cuba, or in South America. The true mahogany reaches diameters of from 4 to 6 feet and heights of 100 feet or more. The logs which are produced now do not average as large as did those produced earlier, because the best of the accessible timber has been removed.

Almost nothing is known regarding the stand of African mahogany, except that, as compared with the present consumption, the supply is almost unlimited. The largest quantities of Senegal mahogany are in the Liberia, Ivory Coast, and Gold Coast territories, while there are large amounts of other species in Kamerun, French Congo, Lagos, southern Nigeria, Spanish Guinea, and smaller amounts in Senegal, Sierra Leone, Angola, Belgian Congo, and Madagascar. African mahogany trees are very large, so that 4 or 5 foot squared logs are common.

The supply of Philippine mahogany (Bataan) available to the larger existing plants is estimated at about 5,400 million board feet.

PRODUCTION OF LUMBER.

Almost all of the Central American and African mahogany cut is exported from the producing countries. Most of it is shipped in the log or hewed into square timbers. Logs are cut by natives, who work either for contractors or directly for the mahogany firms, and the production varies considerably from year to year, depending upon markets, weather conditions (particularly in Central America, where the mahogany logs are taken down to the coast by river floods), and other factors. Logging operations are usually carried on almost entirely by hand labor. A few large concerns use steam or gasoline tractors to haul their logs, but in most operations even the largest logs are pulled to the streams by natives.

The exports of mahogany from South and Central America and the West Indies in 1913, which was a fairly representative year, amounted approximately to 100 million tons or about 50 million board feet. Of this amount the United States used about half, Great Britain about 35 per cent (including that reexported from the United States), and France nearly all of the remainder. The exports of African mahogany in the same year amounted to about 150 million tons, or 75 million board feet, of which about two-thirds went to Great Britain, one-seventh to the United States, and the rest was about equally divided between France and Germany. Liverpool is the great mahogany market of the world, and much of the mahogany which goes there is reexported. In 1913, the United States imported some 21 million board feet of mahogany from Great Britain. This was doubtless principally African mahogany from Liverpool.

The importation of mahogany into the United States is largely controlled by a few companies. The amount of lumber sawed in this country varies considerably from year to year, but for the past five or six years the reported cut has averaged between 20 and 25 million board feet. This may be somewhat less than the actual total cut. Leading States in the production of mahogany lumber are Louisiana (New Orleans), Kentucky (Louisville), Indiana (Indianapolis), Illinois (Chicago), Ohio, and California. From 28 to 42 per cent of the Central American mahogany that is imported is suitable for propellers. The proportion of African mahogany that might be so used can not be estimated, because the character of the timber that may be received is uncertain.

USES FOR THE LUMBER.

Before the war, about 50 million feet of mahogany was used each year in the United States. Thirty-six per cent of this was used for furniture, 17 per cent for musical instruments, 15 per cent for interior finish, 12 per cent for car finish, 11 per cent for fixtures, 3 per cent for caskets and coffins, 2 per cent for ship and boat finish, and small quantities for various other purposes.

SPANISH CEDAR.

(*Cedrela odorata.*)

This species is also called Indian mahogany.

DISTRIBUTION.

Spanish cedar occurs form Tampico, Mexico, southward to Brazil, and through the West Indies. A closely related species, the toona or cedar mahogany (*Cedrela toona*), grows in the East Indies.

USE IN AIRCRAFT.

Spanish cedar, being light, durable, easily worked, and strong for its weight, makes excellent ply wood, and has been used to a considerable extent for thin planking for flying boats and floats.

SUPPLY OF TIMBER.

This species occurs in about the same situations as mahogany, with which it is associated in the range of the latter. It is scattered through mixed stands, but is probably somewhat more abundant than the mahogany. Cedar trees reach great size, diameters up to 6 feet being not uncommon. Information is not available regarding the amount of standing cedar except that it is known to be large.

PRODUCTION OF LUMBER.

Spanish cedar is frequently cut in connection with mahogany. Cedar logs are often used in rafts to help keep the heavier mahogany logs afloat. Considerable quantities of cedar are logged independently. Data on the total production of Spanish cedar are not at hand. From 15 to 20 million feet is imported in the log into the United States in normal years, while the imports of sawed lumber, chiefly from Cuba, are estimated at about 10 million feet a year. Large quantities go also to Liverpool, London, and Hamburg. Since only selected material is usually imported, a very large proportion of it would be suitable for use in aircraft. Our largest imports are from Cuba. Other countries which supply considerable quanties are Brazil, Mexico, British Honduras, Colombia, Nicaragua, Costa Rica, Panama, and Dutch Guiana.

USES FOR THE LUMBER.

Almost the entire output of Spanish cedar is normally made into cigar boxes. In the United States more than 99 per cent of the cedar used goes to that industry.

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REPORT No. 68

THE EFFECT OF KILN DRYING ON THE STRENGTH OF AIRPLANE WOODS

Prepared in the Forest Products Laboratory of the Forest Service
(In cooperation with the University of Wisconsin)

BY

T. R. C. WILSON, Engineer in Forest Products

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FOREWORD.

This monograph is one of a series contributed by the Forest Products Laboratory, which is maintained at Madison, Wis., by the Forest Service, United States Department of Agriculture, in cooperation with the University of Wisconsin.

The investigations described have been carried out with the aid of funds provided by the War and Navy Departments, and the results have been used by these departments in connection with specifications for the kiln drying of airplane material.

The author desires to make acknowledgment to Mr. H. D. Tiemann, specialist in kiln drying, and to Mr. J. A. Newlin, in charge section of timber mechanics, whose extensive investigations of kiln drying and the strength of timber have been basic in planning the tests and analyzing the data described and presented. Messrs. L. A. Welo, C. A. Plaskett, R. P. A. Johnson, and H. J. Rosenthal aided in preparation of material, superintendence of tests and tabulations and analysis of data and their persevering, painstaking, and loyal efforts are acknowledged.

It is also desired to acknowledge cooperation of numerous lumber associations and companies in furnishing material for test.

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REPORT No. 68.

THE EFFECT OF KILN DRYING ON THE STRENGTH OF AIRPLANE WOODS.

By the Forest Products Laboratory.

SUMMARY OF GENERAL CONCLUSIONS.

The general conclusions stated below are the outcome of a series of tests which included 26 species, approximately 100 kiln runs, and over 100,000 mechanical tests. The series was undertaken in cooperation with the War and Navy Departments, and in continuance of earlier investigations on the basis of which the Forest Products Laboratory had drafted, for the War Department, Signal Corps Specification 20500, General Kiln-drying Process for Airplane Stock.[1]

This specification was based on the results of tests of Sitka spruce and white ash material representing three preliminary kiln runs at the laboratory, and on the general knowledge of kiln drying and the properties of wood which the researches of the laboratory in earlier years had developed. The material for the first tests had been arranged for before the United States entered the war, as it was antecipated that kiln drying of airplane stock would become necessary; and the preliminary runs antedated the adoption by the Government of its aircraft program. Signal Corps Specification 20500 was submitted to the War Department in July, 1917. While its adoption as an emergency measure was believed entirely justified, additional tests of its safety for spruce and ash and of its applicability to many other species were considered essential. It was desirable also to ascertain the possibility of using more rapid processes. The present monograph presents results of the tests made for these purposes.

The general conclusions reached are:

1. That wood may have its strength properties, particularly toughness or resistance to shock, quite seriously damaged without any *visible* evidence of such damage. Hence, *appearance* of the material can not, where maximum strength is essential, be accepted as the sole basis of judgment of the effect of a drying process on wood.

2. That the effect of a given process is not the same on all species of wood.

3. That apparently a given process may be entirely safe for some but quite detrimental to other material of a species.

4. That proper kiln drying produces material fully equal in all strength properties to that resulting from air drying under the most favorable conditions.

5. That specification 20500–A of the Bureau of Aircraft Production (Table 1 or 2 as specified) can in most cases be expected to produce material fully equal to air-dried.

6. That best results (with respect to strength properties) on Douglas fir will result from the use of somewhat milder drying conditions than those laid down in Specification 20500–A (Table 1). Table 2 of this specification (temperatures 105° F. initial to 135° F. final and relative humidities 85 per cent initial to 40 per cent final) is recommended for drying Douglas fir.

7. That in some species there is apparently no relation between drying temperatures up to 180° F. and the strength properties of the dry material. Such a conclusion, however, needs further confirmation, and temperatures higher than those of Specification 20500–A have not been recommended.

This work has been done under the necessity of getting results as quickly as possible and with the primary object of checking the safety of the general kiln-drying specifications when applied to the drying of airplane lumber on a commercial scale, together with the more or less incidental object of ascertaining if conditions adapted to more rapid drying could be used. Under these circumstances it has not been possible to investigate the subject in the fundamental

[1] Now with some slight modification Specification 20500–A of the Bureau of Aircraft Production.

way which it merits. Completion of the work already begun is contemplated and it is hoped to be able later to carry out experiments to determine the effect of the various factors involved, both separately and in combination, and to ascertain the maximum temperature and minimum humidity that can be safely applied at any stage of the drying process. It is hoped also to carry on comprehensive investigations of the closely related subject of the bending of wood, for the purpose of determining the steaming or other processes best adapted to successful bending and to secure more accurate knowledge of the effect of such processes on the strength of the wood.

NECESSITY FOR KILN DRYING.

Previous to the entrance of the United States into the war aircraft engineers had not encouraged the use of other than air-seasoned wood, particularly for those parts requiring the maximum strength. It had not been believed that it was possible for material to be properly prepared for such exacting service in any other way than by air seasoning over a period of several months or even years, depending on the size of the stock and on the climatic conditions at the point where the seasoning took place. The use of kiln-dried material had been tabooed because it had not been demonstrated that optimum results with respect to the strength properties could be secured through kiln drying. Some of the prejudice against kiln drying was undoubtedly due to acquaintance or experience with material which had been improperly kiln dried and hence greatly damaged.

Upon the adoption by our Government of an aircraft production program of great magnitude it was easy to be seen that the stock of air-dried material of the species then accepted for aircraft construction would be exhausted before even a fraction of the production planned for the first year could be accomplished. Hence, the kiln drying of material for airplanes became imperative. The prime requisite was to find or develop methods of kiln drying which would assure material of maximum strength properties. The problem of cutting the period of drying to the minimum was not so important, as it was the opinion that a period of from one to two months for the drying of such species as spruce would answer, if necessary.

PREVIOUS INVESTIGATIONS.

For some 12 years previous to this time the Forest Service had been carrying on investigations of the best types of kiln construction and methods of kiln operation to produce dry stock of maximum quality. These investigations had resulted in the invention, patenting, and dedication to public use of a new type of dry kiln in which excellent control of the important factors of temperature, humidity, and circulation could be secured. However, few of the species of importance in airplane construction had been included in these kiln-drying investigations. Also, the effort had been largely directed toward preventing the great losses from checking, casehardening, hollow-horning, and the like, which in many commercial drying operations had been excessive; and consequently tests had not been made to determine whether material having the maximum strength properties was being secured. However, about the time the kiln-drying studies were first started a very carefully planned and executed series of tests had been made to determine the effect, on strength, of exposure for various periods of time to dry air and to steam, both at various temperatures and pressures. These experiments [1] were on loblolly pine, white ash, and red oak. Additional knowledge of the effects of various temperatures had been gained from the results of tests of material which had been subjected to various steps involved in the application of preservative treatment.

Foreseeing the necessity for knowledge of the effect of kiln-drying operations on the strength of airplane woods, the Forest Products Laboratory before the declaration of war arranged to secure a quantity of partially air-dry spruce and white ash. Strength tests made on material dried in three preliminary kiln runs with a range of temperatures and humidities, indicated that spruce and ash could be successfully and safely kiln dried by using moderate temperatures and fairly high relative humidities, with careful control of kiln conditions. That material might be seriously damaged in strength properties without displaying visible signs of deteri-

[1] A résumé of the results was published in the Lumber World Review, Apr. 10, 1918.

oration was also indicated. This denoted that perfection of appearance did not constitute a safe criterion for the acceptance of material for exacting uses such as aircraft construction, and emphasized the need for standardization of drying practice and the specifying of limiting conditions to be used.

ADOPTION OF SPECIFICATIONS AND BEGINNING AND SCOPE OF PRESENT WORK.

With these tests and the previous experience of the laboratory in many lines as a basis, Signal Corps Specification 20500 (now with some slight modification Bureau of Aircraft Production Specification 20500–A) was drawn up. The general problem of kiln drying airplane stock, however, was by no means solved. Although the tests which had been made were sufficiently extensive to form, in the existing emergency, a basis of kiln-drying specifications, it was very desirable to get a further check upon their applicability through additional tests. It was also desirable to determine if it would be possible to use conditions adapted to more rapid drying. Moreover, there were a considerable number of species which were looked upon as suitable substitutes for spruce, ash, and the other woods which experience had already shown to be adapted to aircraft construction. It was regarded as essential that safe methods of drying these species be developed. In addition to this, the laboratory was undertaking tests of numerous features of airplane construction and it was necessary to have dry material for use in these tests.

The work has now covered 26 [1] species, with approximately 100 kiln runs and with some 100,000 mechanical tests to determine the effect of the processes. It is the purpose of this monograph to set forth in detail the methods used, to give in considerable fullness the data secured and conclusions drawn, and thus to make available information for the guidance of those engaged in aircraft construction and others who may be interested in kiln drying wood in such a manner as to retain the maximum strength.

BASIS OF TESTS AND COMPARISONS.

Since kiln drying was to take the place of extended periods of air seasoning, it was but natural to adopt air drying as a basis by which to judge the effect of kiln drying. It might seem to one not well acquainted with the phenomena revealed by tests of strength properties of wood that it would be feasible to kiln dry a given lot of material, make tests upon it, and compare directly with the strength of air-dry material of the same species, as determined by previous tests. Such a method, it is true, might suffice to detect any severe damage or excessive deficiency in strength properties brought about by the drying processes. In the present experiments, however, the aim was to find kiln processes such that the resulting material would be at least equal in strength properties to the same material had it been carefully air seasoned. The decision as to whether this has been accomplished requires more exact comparisons than can be obtained by the method given above. Also in such work it is desirable to be able to distinguish small differences in the effect of two or more different treatments in order to discover the tendency of a change in the treatments.

The study of data derived from some 130,000 tests on 129 different species of native woods tested at the Forest Products Laboratory previous to the beginning of this work has shown something of the variability that may be expected. It has been found, for instance, that even when as many as possible of the factors contributing to the variation of timber are under control, the average of material from a tree selected at random would be expected to differ from a true average of the species by from 7 to 15 per cent, depending upon which of several important strength properties was considered. The variation of individual specimens is, of course, much greater. Consequently, it is essential to make certain that the material subjected to any treatment whose effect is to be found is as inherently like that with which it is to be compared as possible. In other words, no very close estimate of the effect of kiln drying upon the strength is possible from comparisons of the properties of two lots of material, one being kiln dried and the other air dried, and both selected at random.

[1] Data and information on but a part of these species are available and included herein.

The problem presents two alternatives. One is to divide the green stock of a given tree or trees into two lots, one of which is tested after kiln drying and the other after air drying. This involves a delay in the analysis until the air drying is complete and the tests made, and was deemed impracticable because of the demand for immediate information.

The second alternative is to make a comparison with the results previously obtained from material of the same species and tested in both the green and the air-dry conditions. On the basis of this comparison a conclusion may be drawn as to whether kiln drying has produced as favorable a change in properties as had been found, from the previous tests, to result from air drying. This second method is, of course, the best adapted to securing quick results. On the other hand, it does not, for reasons which have been mentioned and which will be further discussed later, justify as definite and certain conclusions as the first.

The plan actually followed was a combination of the two alternatives.

The material for testing was brought to the laboratory in log form, and was there cut up into three lots. The first was tested green, the second after kiln drying, and the third after thorough air seasoning. Methods of making this division are further discussed under "Preparation of Material."

As soon as the tests on kiln-dried material were available they were analyzed and preliminary conclusions drawn from a comparison with previously air-dried material of the same species. This can be safely done only on the part of those who are experienced and familiar with strength values and particularly familar with the variations that are likely to be met with in stock of a given species grown in different localities. If the kiln-dried material proves to be greatly superior or greatly inferior it is safe to say positively that it would also have been superior or inferior to stock of the same tree air dried. If, however, the differences turn out to be small and less than the probable variation of an average of the strength property, definite conclusions are not possible. This analysis is, therefore, regarded as preliminary and final conclusions are withheld until air-dry material from the same trees and parts of trees has been tested. The comparisons then possible are known to be free of some of the factors enumerated below and the rest can be adjusted for or can be reduced in importance by working with a large number of tests. Where this has been done the difference in strength properties between kiln-dried and air-dried stock and between stock dried under different kiln conditions can be stated, with considerable assurance, to be due to differences in drying conditions only.

VARIABLES AFFECTING RESULTS.

The factors which affect test results and contribute to their variability may be enumerated as follows:

(1) Defects (knots, decay, shakes, etc.).
(2) Density.
(3) Species.
(4) Moisture content and distribution.
(5) Rate of testing.
(6) Temperature at time of test.
(7) Position in tree.
(8) Tree characteristics (varying with locality of growth, soil, elevation, etc.).
(9) Unexplained variations (usually following the laws of probability).

These factors must be so handled that their effects will not be mistaken for the effect of the kiln-drying process. The effects of these factors are eliminated from comparisons in the following manner:

All pieces having visible defects which it is evident would lessen their strength are discarded at the outset. Inspection is also made after test, since some defects are likely not to be revealed until the specimen has failed.

Regarding density and position in the tree, fairly general relations have been deduced from the extensive investigations previously made. It is a general rule that the strength properties of wood of any species vary directly as some power of the density; that the density, and therefore the strength, decreases with height from ground at growth (spruce seems to be an exception to

this); and that there is a considerable but unpredictable variation between strength and distance from the pith of the tree. Provided the test specimens come from the same height in the tree and the same region of annual growth, there does not seem to be much difference in strength with regard to cardinal direction in the living tree.

It is evident, then, that the influence of density, position in tree, and tree characteristics can be eliminated from comparisons, as far as the kiln-drying work is concerned, by selecting material for test in the green, kiln-dried, and air-dried conditions, not only from the same tree but also from its corresponding parts. The existence of tree characteristics also makes it desirable that several trees be represented in each kiln run. It is also found that unexplained variations are such as to necessitate that each tree be represented in each group (green, air-dried, and kiln-dried) by a considerable number of specimens.

The effect of moisture content and distribution could be eliminated by bringing the kiln and air-dried material to the same moisture content before test. This, however, requires an excessive amount of time and it is found more feasible to allow for comparatively small differences in moisture content by making adjustments of the data. These adjustments will be discussed later.

Differences in moisture content between parts of the same specimen are avoided by allowing a period of air seasoning after the kiln drying, thus bringing the moisture in the material to practically uniform distribution. Material which is air dried is not tested until it has reached a practically constant weight and the moisture content has become approximately uniform.

The effects of rate of test and temperature at time of test are cared for by properly standardized testing methods.

MECHANICAL TESTS AND THE PROPERTIES DETERMINED FROM THEM.

The standard tests made on wood at the Forest Products Laboratory and the mechanical properties determined from them are:

Static bending.
- Fiber stress at elastic limit.
- Modulus of rupture.
- Modulus of elasticity.
- Work to elastic limit.
- Work to maximum load.
- Total work.

Impact bending.
- Fiber stress at elastic limit.
- Modulus of elasticity.
- Work in bending to elastic limit.
- Height of drop to failure (50-pound hammer).

Compression parallel to grain.
- Fiber stress at elastic limit.
- Crushing strength.
- Modulus of elasticity.

Compression perpendicular to grain.
- Fiber stress at elastic limit.

Shearing strength parallel to grain.
- Radial.[1]
- Tangential.[1]

Cleavage.
- Radial.[1]
- Tangential.[1]

Tension perpendicular to grain.
- Radial.[1]
- Tangential.[1]

Hardness.
- End.
- Radial.
- Tangential.

[1] The terms "radial" and "tangential" refer to the surface of failure. Radial tension is tension perpendicular to the radial surface.

It may not appear necessary to perform all of these tests on the green, kiln-dried, and air-dried material in order to get a sufficiently reliable basis for the determination of the effect of kiln drying. On the other hand, it would not do to select one kind of test on one property and assume that if the kiln dried stock proved to be superior or inferior to air-dried, all the other properties would also be superior or inferior. The several properties may very well, and do in fact, prove to be affected in different ways by the various conditions of seasoning. This phenomenon is amply illustrated by data presented later.

PROPERTIES ON WHICH ANALYSIS IS BASED AND THEIR SIGNIFICANCE.

The analysis of the effect of kiln-drying is, therefore, based on the tests which bring out the properties deemed most important in airplane construction; namely, static and impact bending and compression parallel to grain; although all of the tests are made because the tests of lesser importance can be made at a comparatively low cost and serve at times as a check on the conclusion reached from a study of the principal test data.

The properties chosen for principal attention in the analysis are five in number. They are: Modulus of rupture, modulus of elasticity, and work to maximum load, obtained from the static-bending test; height of drop, obtained from the impact-bending test; and maximum crushing strength, obtained from the compression-parallel-to-grain test.

By modulus of rupture is meant the computed fiber stress in the outermost fibers of the the beam at the maximum load. It is a measure of the ability of a beam to support a slowly applied load for a very short time. It is not a true fiber stress, since the formula by which it is computed is exactly applicable only within the elastic limit. The term is, however, universally accepted and the values are quite comparable for various species and sizes of lumber. It is, moreover, a definitely measurable quantity which does not depend to any extent on any personal factor as does, for instance, fiber stress at elastic limit.

The modulus of elasticity is a measure of the stiffness or rigidity, of a material, and is of value in computing the deflections of joists, beams, and stringers, and safe loads for columns. Although it is derived from the static bending test it is directly applicable to columns as well as beams.

Work to maximum load represents the ability of a wooden part to absorb shock with a slight permanent or semi-permanent deformation with some injury to the wood, and is a measure of the combined strength and toughness of a material under bending stresses. It is one of the most important properties as far as airplane wood is concerned.

Height of drop is the vertical fall of a 50-pound hammer causing complete failure under the impact-bending test, and represents a quality that is important in members which are occasionally stressed beyond the elastic limit. It is a very variable quantity but ranks with work to maximum load in importance as a measure of the suitability of a wood for airplane use.

The value of maximum crushing strength, as obtained from the compression-parallel-to-grain test, lies in the possibility of estimating the strength of parts used as columns. It is a very simple test and is frequently the only one used in studying the effect of a treatment or process on wood. However, it does not necessarily follow that others are affected in the same way and, particularly not with respect to the very important properties of work to maximum load and height of drop. These latter are measures of toughness, or shock resistance, which quality is not brought out by the compression-parallel-to-grain test.[1]

The manner of conducting these and the minor tests and the significance of each of the properties is discussed in various circulars and bulletins of the Forest Service of the United States Department of Agriculture.[2]

[1] See p. 37 and footnote thereto.

[2] See particularly Forest Service Circular 38 (Revised) and Bulletin 556 of the United States Department of Agriculture. See also "Working Plan for Project 124," included as an appendix in The Mechanical Properties of Wood, by S. J. Record, published by John Wiley & Sons.

PREPARATION OF MATERIAL.

SELECTING, CUTTING, AND MATCHING OF STOCK.

The necessity for having material so selected that comparisons will be only between groups which consist of material inherently alike has been pointed out. The method of cutting logs and selecting material will be illustrated for each of several species. Great care has at all times been taken to make certain that kiln-dried material is as inherently like the green and air-dried to which it is compared as possible.

In most cases the material for test was selected in the woods or from log yards and sent to the laboratory in log form. There it was stored on skids in the yard until required. In general, species which were in use or considered as substitutes for spruce in wing beams, struts, etc., were cut into 2½ or 3 inch planks, in which sizes the material was kiln-dried. Species looked upon as promising for propeller woods were sawed into 1-inch lumber and kiln-dried in this thickness.

Test specimens were 2 by 2 inches in cross section for those species dried in the 2½ or 3 inch thickness. Bending specimens were 30 inches long and were tested with center load on a span of 28 inches. Specimens from the species dried in 1-inch thickness were ¾ by 2 inches in section. Bending specimens were 20 inches long and were tested with load at the center of an 18-inch span.

Specimens for test while green were cut and planed to size at the time of cutting material from the log. Specimens for test after air drying were at the same time cut roughly to size and stored for drying. Specimens to represent the kiln-dried material were not cut until after the kiln-drying was completed. Specimens which were to be air-dried were carefully piled in a shed where they were well up off the ground, were sheltered from the sun and from precipitation, and were subjected to very free circulation of air. Ends of these specimens were dipped in melted paraffin to retard drying from the end. The endeavor was to give them the best possible environment for air-drying.

Each shipment of a species is considered a unit. It has not been possible to get all shipments of a species uniform as to size and length of logs, etc. Logs of one species differ greatly, of course, from those of another in size and character. The method of grouping material is influenced by a number of factors, such as size of logs, number of kiln runs in which each log is to be represented, method of sawing (plain or quarter-sawed), thickness of material to be dried, and number of logs in shipment. Consequently it was impossible to adopt a single standard plan for cutting, marking, and grouping; each shipment had to be studied separately and the method best suited to it adopted.

Figure 1 (A) to (E) illustrates several of the methods of cutting logs. Figure 1 (E) shows how the logs of Sitka spruce of shipment 504 were divided. These logs were so large that it was necessary to split them before they could be sawed. They were first split into quarters. Each quarter was then split circumferentially into two pieces and the outer one of these pieces was again split radially into two pieces. The resulting 12 pieces were sawed as shown. The central flitches HL and MK were cut into sticks 2½ by 2½ inches in the rough. Matched specimens for test in the green and air-dry conditions were provided in accordance with the following scheme: With an 8-foot log or double-length bolt as a unit, two flitches extending through the tree in one direction, as in figure 1 (B), or in each of two directions, as in figure 1 (E), are cut into 2½ by 2½ inch sticks. These are numbered as in figures 1 (B) and (E), the number consisting of a letter and a figure, as H3, L6, etc. These sticks are then grouped for test as follows:

STICK NUMBERS.

Lower bolt	1	4, 5		8, 9	Tested green.
Upper bolt	2, 3		6, 7	etc.	
Lower bolt	2, 3		6, 7		Tested after air-drying.
Upper bolt	1	4, 5		8, 9	

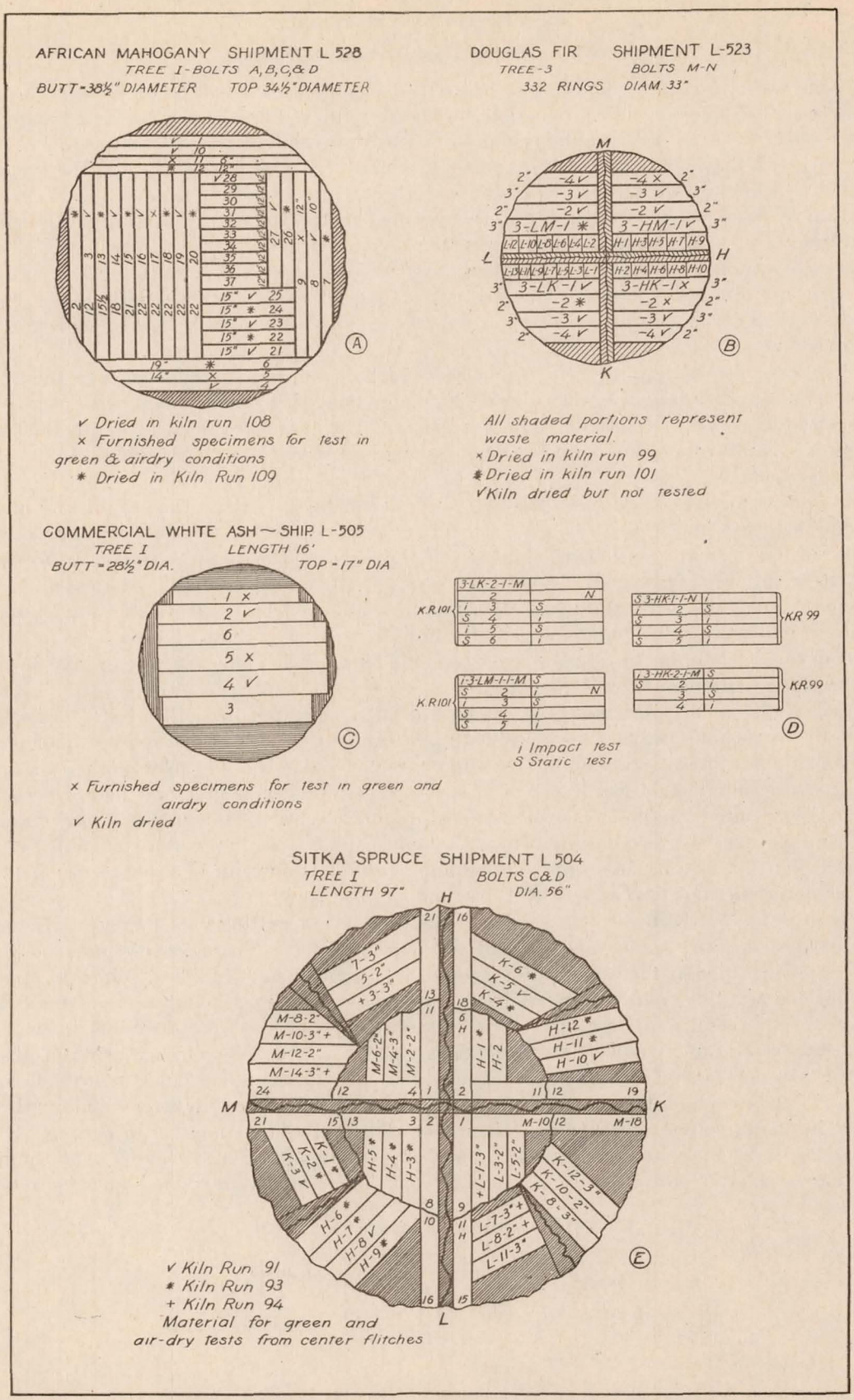


FIG. 1.—Method of cutting logs into lumber for kiln drying and into test specimens.

That is, two composite bolts are formed, each including half the sticks from the upper bolt and half those from the lower bolt. The sticks of one of these composite bolts are tested green and those from the other after air-drying.

Figure 1 (D) shows how planks are divided into sticks for static and impact-bending tests after having been dried in the kilns. In general, half of the sticks of any given group—green, air-dried, or from any kiln run—are tested in static bending and half in impact. One specimen from each stick is tested in compression parallel to grain. One-half of the static-bending sticks furnish smaller specimens for compression-perpendicular-to-grain tests; the other half give specimens for hardness tests. Shear, cleavage, and tension-perpendicular-to-grain specimens are taken from impact-bending sticks.

Figure 1 (A) and (C) are cutting diagrams as used for African mahogany and white ash, and are typical of diagrams for logs which were cut into 1-inch material or were not sufficiently large to be cut as in figure 1 (B) or (E).

INSPECTION OF STOCK.

Immediately previous to being placed in the kiln all material is very carefully inspected and any defects and imperfections noted and marked on the piece or made a matter of record. On removal from the kiln it is again inspected and record made of any increase in the previously noted defects, such as extension of shakes, increase of checks, or loosening of knots; also of warping and cupping, the development of new checks, etc. It is also examined for case-hardening.

KILN DRYING AND TESTING.

Following the initial inspection the material is placed in experimental kilns and dried. On removal from the kilns it is stored for a brief period, after which the standard tests as previously enumerated are made.

METHODS OF ANALYSIS.

We come now to a discussion of the actual comparison of the test data on material dried under different kiln conditions and in the air. Because of the several influencing factors which have been enumerated, this comparison can not be made directly from a table of properties in which these properties are grouped according to the seasoning conditions. The reason is that in the case of the preliminary analysis the air-dried stock used for comparison was not inherently like that kiln-dried. The trees and the parts of the trees are necessarily different and the localities of growth are, in general, different also. In the final analysis the tests of the several kiln runs and the air-dried were on matched stock; that is, on stock inherently the same. Thus the source of possible error in making a direct comparison introduced by unlike stock falls away. However, differences in moisture content still usually exist at the time of test.

IMPROVEMENT RATIOS.

In attempting to find for use in the preliminary analysis some basis of comparison which would, as far as possible, avoid the errors resulting from inherently different material in the groups compared, study of the available data showed that the *change* in properties which is produced by drying is in general somewhat less variable than the strength values. Accordingly, it was believed that the effect of kiln drying could be better judged by comparing the change which it produced with the corresponding change produced by air drying than by comparing strength values of the kiln-dried and air-dried material. The mathematical measure of this change is defined as an "improvement ratio."

$$\text{Improvement ratio} = \frac{\text{Strength value for kiln or air dried material}}{\text{Same strength value for matched green material}}$$

Early tests of the effect of moisture on the strength properties had shown that in one species, at least, the effect of moisture change was practically independent of the specific gravity of the wood. On the other hand, the strength properties are very largely influenced by the specific gravity. Although the relation of specific gravity to strength has been the subject of considerable study and important principles have been deduced, it is not possible to make adjustment of strength figures for differences in specific gravity with sufficient exactness for

the present purpose. Hence, it seems that comparisons are likely to be less affected by differences in specific gravity if based on improvement ratios than if based on the strength properties themselves.

ADJUSTMENT FOR DIFFERENCES OF MOISTURE CONTENT.

In some instances the strength properties of wood change very rapidly with changes in moisture. Some strength properties of some species are nearly tripled in drying from the green condition to about 8 per cent moisture. In other instances, however, the strength properties are decreased in drying. After wood has passed the fiber-saturation point,[1] a change of 1 per cent in the moisture content may produce as much as 7 or 8 per cent change in the strength value. Consequently, since it is impracticable to bring the various groups of material which are to be compared to the same moisture content before test, it is essential to the accuracy of comparisons that careful attention be given to adjustment of strength values for differences of moisture content.

Several years ago a rather comprehensive study of the relation of moisture content to the strength of wood was carried out by the Forest Service at laboratories then maintained at Yale University.[2] This investigation, however, covered comparatively few species, and not all the strength properties of these. In taking up the analysis of the data on the effect of kiln drying on strength, the need of a general moisture-strength law which would be applicable to all species and all properties became apparent. For the purpose of developing such a law the existing data were very carefully reviewed.

Figure 2, taken from Forest Service Bulletin 70, illustrates the relation between moisture and several strength properties of red spruce. The graph for modulus of rupture is seen to be a curve from zero to about 30.5 per cent moisture, beyond which it is a straight horizontal line. This shows that as moisture increases strength decreases until a point is reached where there is no further decrease. This point (30.5 per cent in this case) is termed the fiber-saturation point. At this point the cell walls are completely saturated, but there is no free or excess water in the pores of the cells.

In studying data as given in Forest Service Circular 108 and Forest Service Bulletin 70 on the several species and properties, it was found that when the logarithm of the strength property was plotted against the percentage moisture the points could be averaged, with but comparatively little error, by a straight line. This was so consistently true that the application of the principle involved to other species and to other properties was thought to be justified. The relation as found may be stated mathematically as follows:

$$S = C \times 10^{AM}$$

where S is the strength value at any moisture content, M, below the fiber-saturation point, and C and A are empirical factors. It has been assumed that the type of curve represented by the above equation is applicable to all properties, to all species, and to all drying conditions. The differences between these various curves are represented by the constants (C and A) which adapt the type equation to specific instances. These constants for any specific case are derived from the data to which the equation is to be applied. The following equation, derived from that given above, is conveniently applicable to improvement ratios:

$$\text{Log } R_2 = \frac{M_s - M_2}{M_s - M_1} \times \text{Log } R_1$$

where M_s = moisture content at fiber-saturation point.
M_1 = moisture content of air-dried or kiln-dried material at time of test.
M_2 = moisture content to which it is desired to adjust improvement ratios.
R_1 = improvement ratio of dry material at moisture content of M_1.
R_2 = improvement ratio adjusted to moisture content M_2.

The factor C has been eliminated in the derivation of this equation. The fraction $\frac{\text{Log } R_1}{M_s - M_1}$ is the value of A. In other words, the value of A for use in the adjustment of a set of data is derived from the data.

[1] See second paragraph following. [2] Results and discussion of these tests are given in Forest Service Circular 108 and Forest Service Bulletin 70.

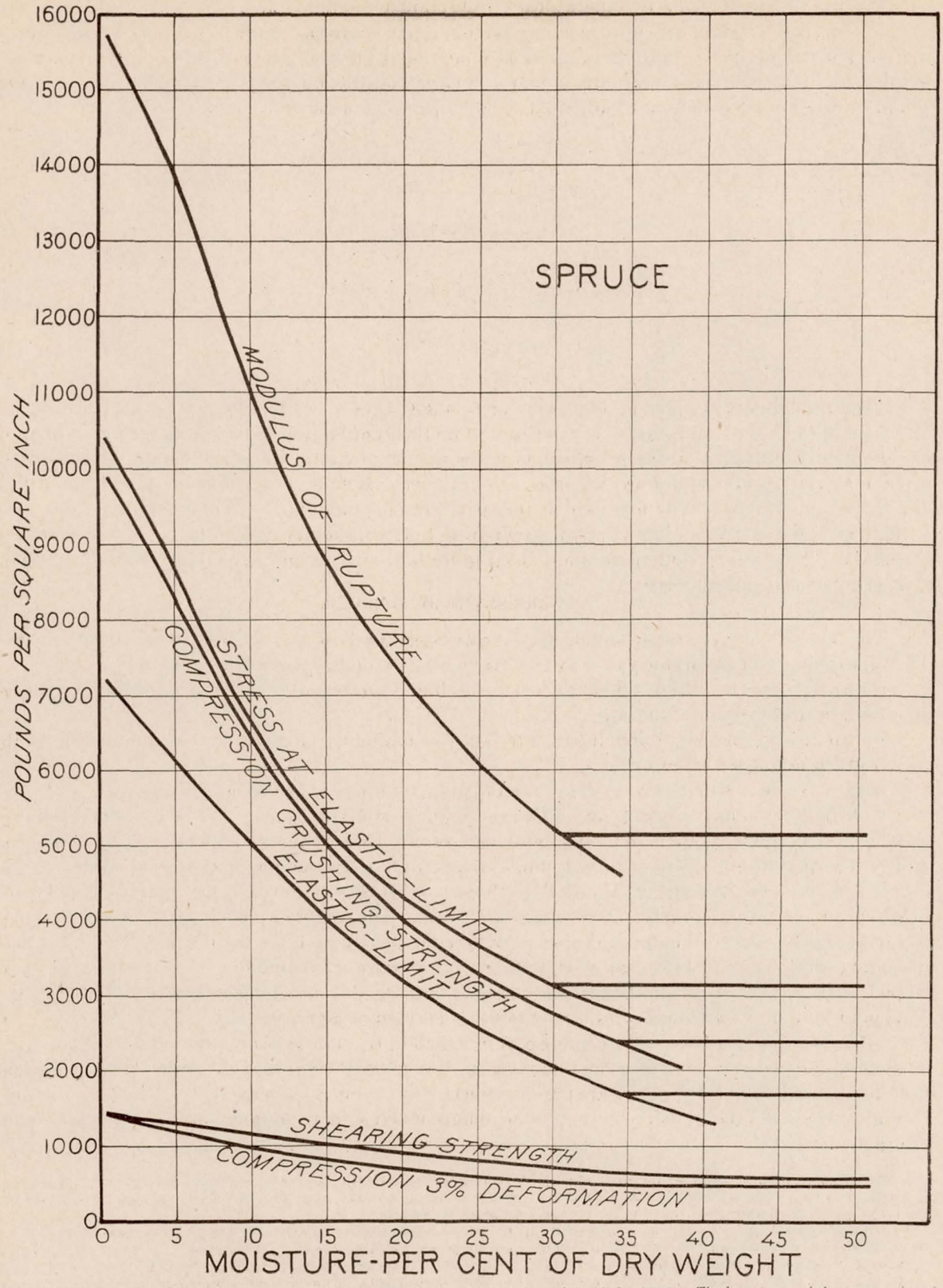


FIG. 2.—Relation between strength values and moisture content for red spruce in various kinds of tests. The lowest curve is for compression at right angles to grain.

The use of this formula is illustrated by the following example:

The average modulus of rupture of a certain group of material tested at 9.0 per cent moisture was 10,240 pounds per square inch. The modulus of rupture of the corresponding green material was 4,890 pounds per square inch. The fiber-saturation point is 23 per cent. What would be the improvement ratio adjusted to 11 per cent moisture?

$$M_s = 23$$
$$M_2 = 11$$
$$M_1 = 9.0$$
$$R_1 = \frac{10240}{4890} = 2.095$$
$$\text{Log } R_2 = \frac{23-11}{23-9.0} \times \log 2.095$$
$$= \frac{12}{14} \times .321 = .275 \qquad \text{and}$$
$$R_2 = 1.88$$

Also, modulus of rupture at 11 per cent $= 4{,}890 \times 1.88 = 9{,}400$ pounds per square inch.

As stated above, improvement ratios and methods of adjusting them for moisture are made use of in preliminary analyses where it is necessary to compare kiln-dried material with air-dried material from a different source. They are also found very convenient in comparing kiln-dried material with the air-dried material actually matching it. These latter groups are seldom at the same moisture content when tested; consequently adjustment for moisture is necessary. This adjustment is made a trifle more easily on improvement ratios than on the strength properties themselves.

DISCUSSION BY SPECIES.[1]

The various species on which tests have been made will now be discussed individually. This discussion will be divided into two parts, corresponding to two groups as follows:

Group 1.—Species on which data are available from tests on matched groups of green, air-dried, and kiln-dried material.

Group 2.—Species on which data are not yet available on air-dried material matching that tested green and after kiln drying.

Group 1 consists of Sitka spruce, Douglas fir, western white pine, and white ash.

Group 2 includes white pine, Norway pine, western hemlock, white fir, Port Orford cedar, bald cypress, Central American mahogany, African mahogany (*khaya* sp.), northern and southern white oak, southern red oak, black walnut, sugar maple, and yellow birch.

The kiln-dried material of the first three species of group 1 will be compared directly to air-dried material matching it. Western white pine will be used as an example of the two methods of analysis. It will first be discussed and analyzed as if tests on the air-dried material matching that which was tested after kiln drying were not available. It will then be discussed on the basis of comparison of kiln-dried material with air-dried which is matched to it. This plan will afford a comparison of the two methods of analysis.

Since group 2 consists of those species in which data from tests of air-dried material matched to that kiln dried are not yet available, conclusions must necessarily be made by the method first illustrated under the discussion of western white pine. Data on the various species of this group are not included. Only conclusions reached and recommendations based thereon are given.

[1] The species names used herein are those official in the United States Forest Service except the following: Central American mahogany (*Swietenia mahagoni*), which is officially termed "mahogany;" African mahogany (*Khaya* sp.), for which no official name has been adopted by the Forest Service; and "commercial white ash," concerning which see footnote, p. 53.

The official common and botanical names for the other species are: Sitka spruce (*Picea sitchensis*), Douglas fir (*Pseudotsuga taxifolia*), western white pine (*Pinus monticola*), Port Orford cedar (*Chamæcyparis lawsoniana*), bald cypress (*Taxodium distichum*), western hemlock (*Tsuga heterophylla*), white pine (*Pinus strobus*), Norway pine (*Pinus resinosa*), white fir (*Abies concolor*), black walnut (*Juglans nigra*), sugar maple (*Acer saccharum*), yellow birch (*Betula lutea*). Other common and botanical names applied to the various species are given in Forest Service Bulletin 17, "Check List of the Forest Trees of the United States."

It is not the function of this monograph to discuss kiln-drying schedules; consequently only such data concerning the drying in these experimental runs as is essential to an understanding and interpretation of the results of the strength tests are included. Neither is it intended that the various graphs of kiln conditions should furnish comparisons of the various processes with respect to rate of drying. For such discussions and comparisons the reader is referred to a monograph by H. D. Tiemann entitled "The Kiln Drying of Wood for Airplanes" and published as one of this series. It is also desired to emphasize the fact that the runs described herein were experimental and are not presented as models, nor necessarily as recommended practice.

SITKA SPRUCE.

Because of the importance of Sitka spruce as an airplane material, more experimental kiln drying has been done on this species than on any other. The results of 13 kiln runs made with different combinations of temperature, humidity, circulation, and other factors which may affect strength properties are available for analysis. The first three runs are those which have been previously mentioned as preliminary. These runs were made on partially air-dried rough plank. Because of the fact that the material tested was quite limited in amount, and the further fact that the other runs have furnished much more comprehensive data, it is unnecessary to present the data on these preliminary runs.

SOURCE OF MATERIAL.

The other 10 runs, on which full data are available, were made on material sent to the laboratory in the log form, in three different shipments.

Shipment 504 consisted of six 8-foot logs from four trees grown in Clatsop County, Oreg. They ranged in diameter from 53 to 77 inches. Trees 1 and 2 were each represented by two 8-foot logs, namely, bolts *c–d* [1] and *i–j* for tree 1, bolts *a–b* and *i–j* for tree 2. Trees 3 and 4 were represented by the *e–f* bolts only. Material from trees 2 and 3 was used in kiln runs 88 and 89, while trees 1 and 4 supplied stock for runs 91, 93, and 94.

Shipment 563 came from Portland, Oreg. Much of the material was used for special drying tests which it is not the purpose to consider here. The shipment furnished material for runs 147 and 148, data and discussion of which are included in this publication.

Shipment 578 consisted of six logs, from as many trees, and varying in diameter from 60 to 66 inches. Trees 1, 4, 5, and 6 were represented by the *a–b* bolts, tree 2 by the *c–d* bolts, and tree 3 by the *e–f* bolts. Trees 2 and 3 furnished material for kiln run 163, while material from the other trees was equally divided between runs 171 and 172.

Previously tested green and air-dried material, with which comparison is made, was secured from one tree from Chehalis County, Wash.

CUTTING AND MARKING.

The cutting and marking of Sitka spruce has been previously described (see pp. 15 and 17) is illustrated in figure 1 (E).

DESCRIPTION OF KILN-DRYING CONDITIONS.

Figure 3 shows graphically the kiln conditions and moisture contents of samples of the stock for runs 88, 89, 91, 93, and 94. Similar data for runs 147, 148, 163, 171, and 172 are shown in figure 4.

Kiln runs 88 and 89.—Kiln runs 88 and 89 were made on stock in the form of planks 3 inches thick and of various widths. The planks were piled flat and open as indicated in figure 5. This figure shows the piling, arrangement of heating coils, condenser coils, spray line, and regulating and measuring instruments for kiln run 89, but those for kiln run 88 were not essentially different. Both of these runs were made in a water-spray kiln. Two-inch stickers were used. and openings of an inch left between the planks of each tier. Kiln run 89 had much the milder

[1] This lettering of bolts is in accordance with the following scheme: Beginning at the stump, each 4 feet of length of the tree is assigned a letter. The 4-foot bolt above the stump is then *a*, the second *b*, etc. The first and second taken together are called *a–b*, the eighth and ninth together *h–i*, etc.

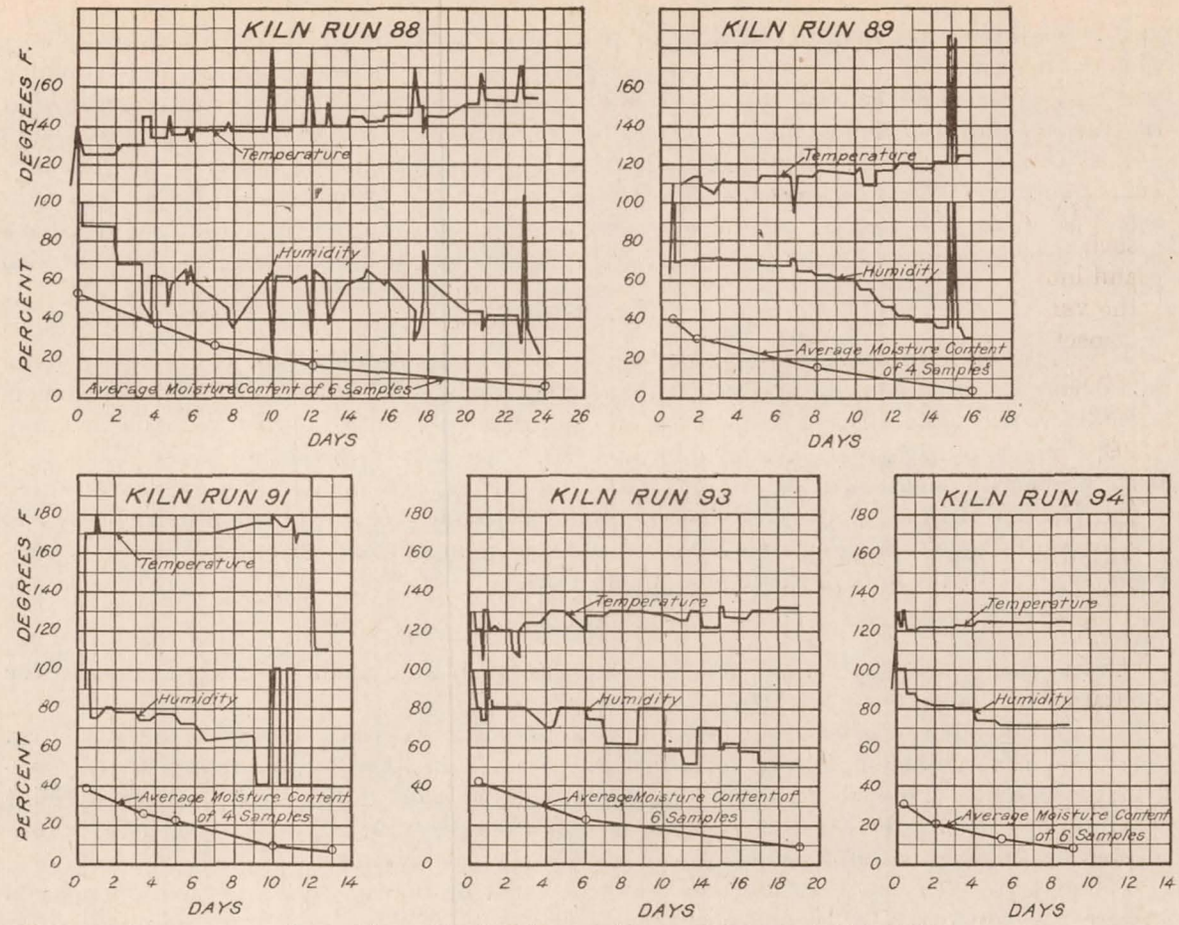


FIG. 3.—Kiln conditions for Sitka spruce, kiln runs 88, 89, 91, 93, 94 (shipment 504).

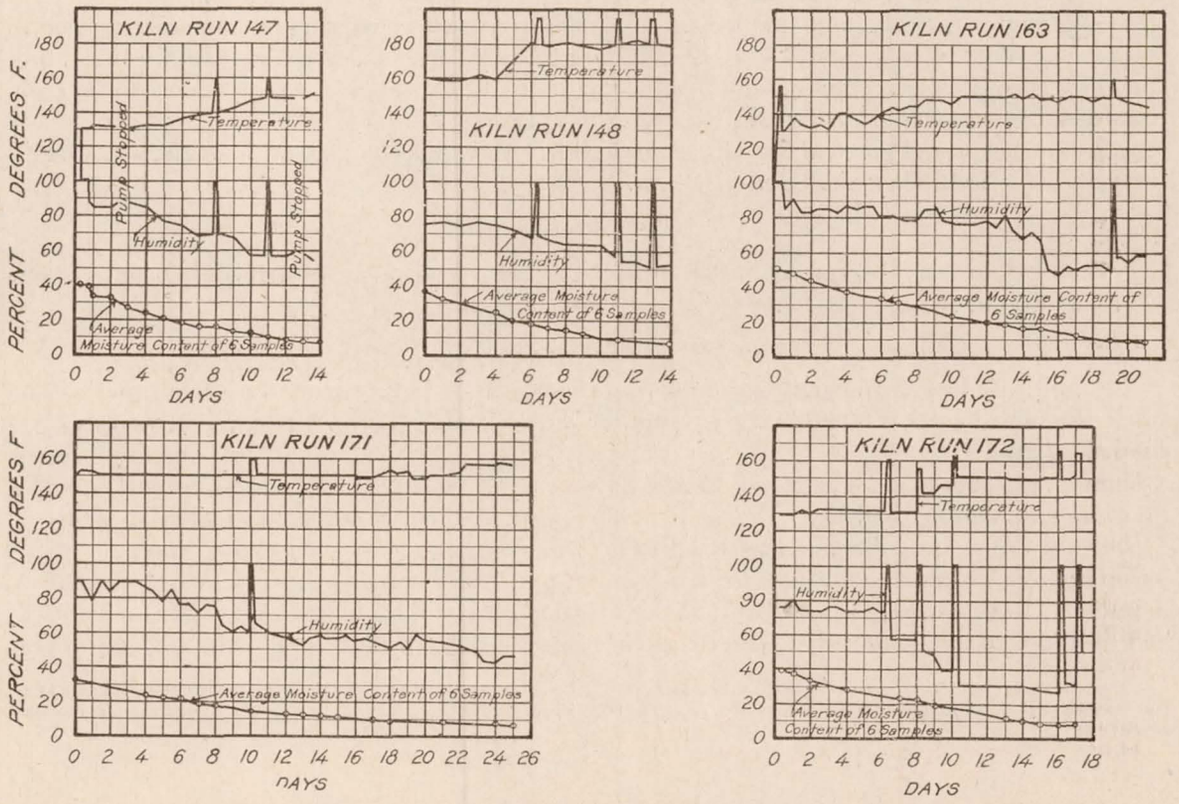


FIG. 4.—Kiln conditions for Sitka spruce, kiln runs 147 and 148 (shipment 563), and runs 163, 171, and 172 (shipment 578).

drying conditions of the two runs, as the temperatures were lower by about 30° F. all through the run and the humidities were higher. (See fig. 3.) In order to get uniform temperatures quickly throughout the planks, runs 88 and 89 were begun with an initial steaming of four or five hours at temperatures of 130° and 150° F., respectively. The very frequent rises in temperature in kiln run 88 (see fig. 3) were due to faulty control apparatus. The stock from both runs appeared to be in excellent condition at the close of the drying, and there was no degrade due to checking, warping, or casehardening. Casehardening had developed during the latter part of the drying

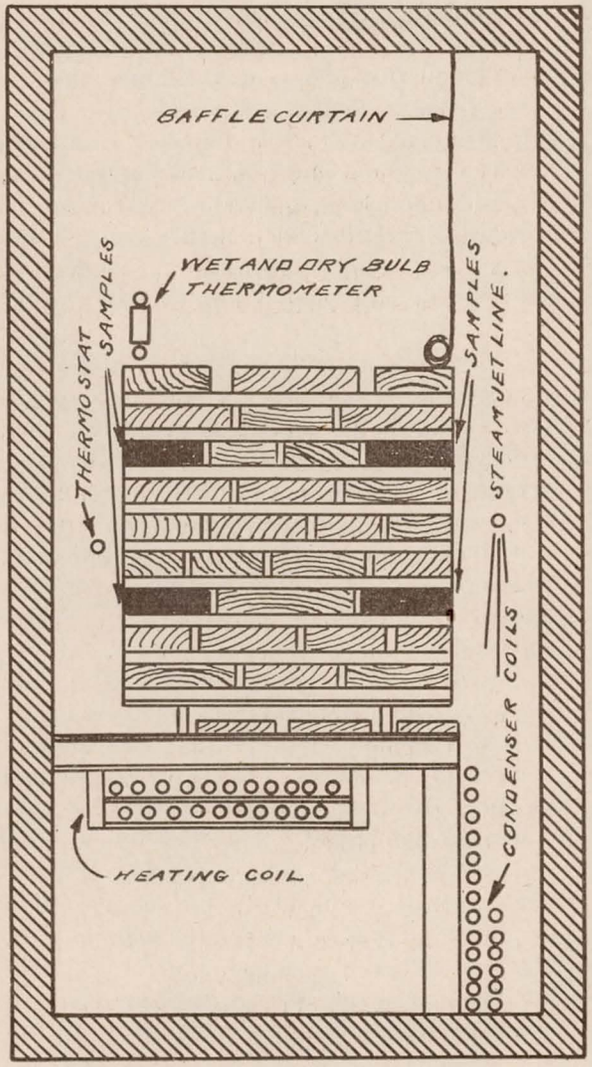


FIG. 5.—Section of kiln and piling diagram, Sitka spruce, kiln run 89.

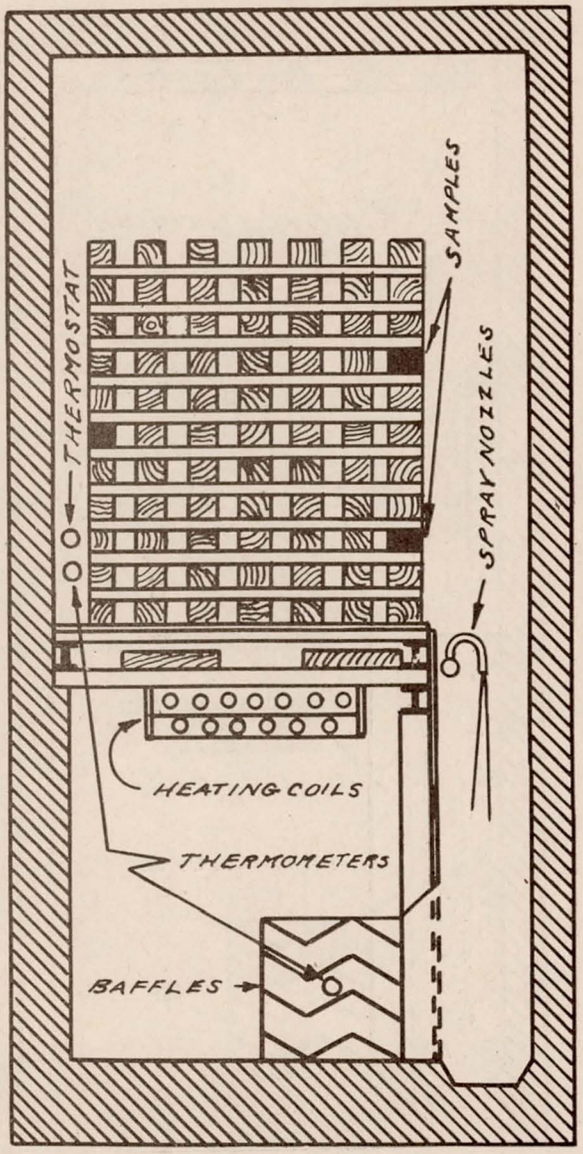


FIG. 6.—Section of kiln and piling diagram, Sitka spruce, kiln run 194.

in both the runs. In run 88 it was relieved by steaming for two hours at 170° F., while in run 89 two steamings at 185° F. were required to do away with the stresses, one of two hours and one of one hour duration.[1]

Kiln runs 91 and 93.—Kiln runs 91 and 93 were made in the same kiln as run 89, so that figure 5, which illustrates the piling and the arrangement of kiln parts for run 89, will suffice for these runs. The stock was of 3-inch thickness, and $1\frac{3}{4}$-inch stickers were used. The kiln loads were small, as only 600 board feet were dried in each.

[1] H. D. Tiemann's monograph, The Kiln Drying of Wood for Airplanes, includes a discussion of the stresses which are formed during drying.

The material in run 91 was steamed twice to relieve casehardening. These steamings were made at 180° F. for two and one-half hours and for one hour.

No casehardening was found at any time in the material dried in run 93, and therefore steaming was unnecessary.

Kiln run 94.—The kiln arrangement and method of piling used in kiln run 94 are shown in figure 6. In this run the stock was dried, not in the form of 3-inch planks, but in sizes suitable for airplane beam planks. The load consisted of 3 by 4, 2 by 3, 2 by 4, and 2 by 5 inch pieces, all 8 feet in length. The 3 by 4 inch pieces were piled as shown in the diagram, using 1¾-inch stickers and leaving about 3 inches between the sticks of each tier. The 2-inch material was similarly arranged in a separate pile behind that shown in the figure, the kiln being twice as long as the sticks to be dried. The same size stickers and spaces were used. The run was mild and practically a repetition of the temperatures and humidities of run 93 (see fig. 3). The final moisture content was 9.6 per cent, and there was no visible degrade nor any casehardening at any time during the run.

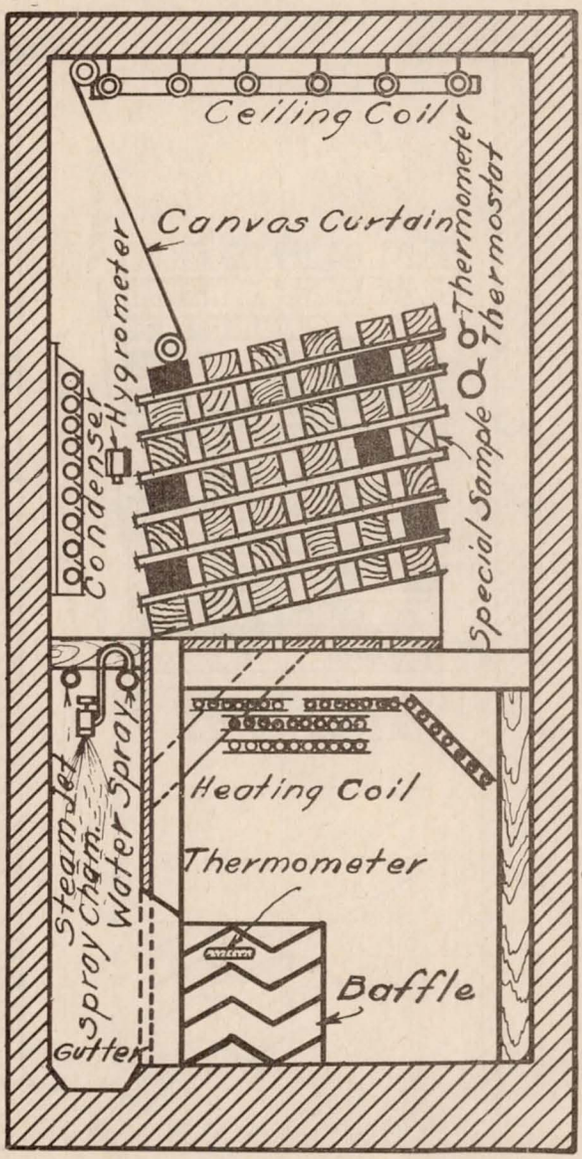


FIG. 7.—Section of kiln showing method of piling Sitka spruce, kiln run 147.

Kiln run 147.—Run 147 was also made on pieces of small size. These were rough-sawed sticks 2½ inches square and 4 feet long. The ends were dipped in an asphalt paint to prevent drying from the ends. The piling was open and on a slant, as shown in figure 7. The material developed slight casehardening, which was relieved by steaming twice at a temperature of 160°, as shown on the temperature and humidity curves of figure 4.

Kiln run 148.—The other kiln run on stock of shipment 563 was numbered 148. This was made for the explicit purpose of finding the effect, on both appearance and strength, of high temperature drying with moderate humidities. The load was a large one for the size of kiln, consisting of 2,400 board feet of 3-inch planks, which were flat-piled with no spaces between the planks. The kiln was of the type shown in figure 6. The kiln conditions and average moisture contents of the samples are shown in figure 4.

Kiln runs 163, 171, and 172.—Of the three kiln runs on stock from shipment 578 the two runs numbered 163 and 172 were practically the same with respect to piling and the temperatures used. Both runs were made in water-spray kilns. The arrangements of the kilns and the locations of the measuring and controlling instruments were practically the same as is shown in figure 6. The stock was in the form of 2½-inch planks, 8 feet long, and varied in width from 6 to 18 inches. The piling was flat, with 1½-inch stickers and with 2-inch spaces between the planks of each tier.

The stock of run 163 was given a preliminary steaming of two hours at 155° F. in order to warm the planks through before drying conditions were established. The temperatures, humidities, and the average moistures for the six samples varied from day to day according to the

curves of figure 4. There was a 2 per cent degrade in this run, due to warping and to surface checking in the sapwood of some of the planks.

Run 171 was a constant-temperature run, the temperature being 150° F. except during the last three days, when it was 156° F.

THE AIR DRYING.

Material of shipment 504, matching that kiln dried in runs 88, 89, 91, 93, and 94, was air dried in the form of sticks 2½ by 2½ inches by 4 feet, the ends being carefully paraffined to prevent end drying. It was dried for about one year, from midsummer 1917 to midsummer 1918 in a shed without artificial heat. The shed was open on the north and closed on the other three sides. The specimens were piled about 7 feet above the ground, midway between the ground and the roof of the shed. The conditions thus secured were considered as favorable for perfect air drying as are obtainable. When stored for drying the average moisture content of the group of sticks matching two of the kiln runs (88 and 89) was about 49.1 per cent, and for another group of sticks matching kiln runs 91, 93, and 94 about 41.5 per cent. The final moisture contents, after the material appeared to have reached constant weight, as indicated by periodic weighing of samples, were found to be very uniform and somewhat higher than was anticipated.[1] For six samples they were 14.0, 14.3, 14.2, 14.3, 14.3, and 14.5 per cent, giving an average of 14.3 per cent. The moisture at the time of test was nearly 2 per cent less, since some time necessarily elapsed from the time of removal from the drying shed, during which time the sticks were stored indoors in a warmer and drier atmosphere.

STRENGTH DATA.

The conclusions which are to be drawn regarding the effect, on the strength of Sitka spruce, of the various conditions of seasoning just described are based on the study of a series of tables giving both the mechanical properties of the various groups of material and the improvement ratios. The ratios are further presented in graph form for the sake of ready intercomparison.

TABLE 1.—*Mechanical properties of Sitka spruce. Tabulation of test data. No adjustment for moisture.*

Properties.	Tree 186. Shipment 325. From Chehalis County, Wash.		Shipment 504. From Clatsop County, Oreg.								
	Green.	Air-dry.	Green matching kiln runs 88, 89.	Air-dry matching kiln runs 88, 89.	Kiln run 88.	Kiln run 89.	Green matching kiln runs 91, 93, 94.	Air-dry matching kiln runs 91, 93, 94.	Kiln run 91.	Kiln run 93.	Kiln run 94.
STATIC BENDING.											
Moisture (per cent) [2]	54.4	8.8	49.1	12.4	9.1	10.7	41.5	12.5	10.7	11.1	9.4
Specific gravity [3]	.329	.353	.346	.377	.380	.369	.338	.367	.362	.366	.368
Fiber stress at elastic limit (lbs. per sq. in.)	2,730	6,520	3,060	5,910	6,870	6,090	3,240	5,780	5,820	6,160	7,320
Fiber stress at maximum load (lbs. per sq. in.)	5,200	10,500	5,040	8,470	10,440	9,110	4,820	8,430	9,220	8,890	10,200
Modulus of elasticity (1,000 lbs. per sq. in.)	1,050	1,410	1,163	1,352	1,551	1,418	1,065	1,394	1,373	1,478	1,517
Work to elastic limit (inch-lbs. per cu. in.)	.43	1.74	.47	1.56	1.71	1.50	.57	1.33	1.43	1.48	2.01
Work to maximum load (inch-lbs. per cu. in.)	5.7	9.2	5.4	7.44	8.3	7.7	5.4	7.34	9.5	6.7	7.6
Work, total (inch-lbs. per cu. in.)	17.9	19.9	17.1	.....	14.6	13.4	13.1	.....	15.4	.....	.....
IMPACT BENDING, 50-POUND HAMMER.											
Moisture (per cent) [2]	73.2	9.0	46.1	13.0	9.1	11.7	44.1	12.2	10.8	10.6	9.2
Specific gravity [3]	.33	.37	.353	.377	.375	.366	.339	.373	.360	.365	.374
Fiber stress at elastic limit (lbs. per sq. in.)	7,220	12,680	8,020	10,120	11,590	10,900	7,690	9,940	10,380	10,710	12,140
Modulus of elasticity (1,000 lbs. per sq. in.)	1,366	1,845	1,307	1,618	1,702	1,650	1,244	1,663	1,696	1,731	1,930
Work to elastic limit (inch-lbs. per cu. in.)	2.2	4.8	2.8	3.5	4.4	4.1	2.7	3.4	3.6	3.7	4.3
Inches drop 50-pound hammer to failure	24.0	29.0	21.0	22.4	24	22	19	19.5	23	21	25
COMPRESSION PARALLEL TO GRAIN.											
Moisture (per cent) [2]	54.4	8.9	49.0	12.5	9.2	10.5	41.6	12.9	10.4	11.7	8.2
Specific gravity [3]	.32	.35	.343	.374	.378	.371	.337	.363	.362	.363	.373
Rings per inch	6.1	8.9	14.8	6.9	16.6	17.4	13.9	7.4	18.4	13.8	14.9
Summerwood (per cent)	20	16	24	34	.....	.....	.....	35	.....	66	55
Fiber stress at elastic limit (lbs. per sq. in.)	1,680	4,980	1,860	.....	5,010	4,530	1,950	.....	4,600	.....	.....
Fiber stress at maximum load (lbs. per sq. in.)	2,280	5,070	2,200	4,680	5,530	5,100	2,190	4,530	5,120	5,400	6,400

[1] Very probably material which is air dried even in such small sizes does not reach its absolute minimum of moisture for several years.
[2] Per cent moisture based on oven-dry weight.
[3] Specific gravity based on oven-dry weight and volume as tested.

TABLE 1.—*Mechanical properties of Sitka spruce. Tabulation of test data. No adjustment for moisture*—Continued.

Properties.	Shipment 563. From Multnomah County, Oreg.				Shipment 578.					
	Green matching kiln run 147.	Kiln run 147.	Green matching kiln run 148.	Kiln run 148.	Green matching kiln run 163.	Kiln run 163.	Green matching kiln run 171.	Kiln run 171.	Green matching kiln run 172.	Kiln-run 172.
STATIC BENDING.										
Moisture (per cent) [1]	40.5	10.3	37.9	11.5	46.2	12.6	41.8	9.9	40.0	10.6
Specific gravity [2]	.400	.425	.397	.424	.338	.364	.362	.382	.368	.381
Fiber stress at elastic limit (lbs. per sq. in.)	3,279	7,582	3,750	7,333	3,410	5,160	3,210	6,910	3,180	7,220
Fiber stress at maximum load (lbs. per sq. in.)	5,967	10,756	6,084	10,942	5,180	8,720	5,160	10,580	5,120	10,520
Modulus of elasticity (1,000 lbs. per sq. in.)	1,444	1,503	1,474	1,685	1,088	1,248	1,083	1,448	1,061	1,403
Work to elastic limit (inch-lbs. per cu. in.)	.....	.....	.62	1.91	.66	1.66	.52	1.87	.55	2.10
Work to maximum load (inch-lbs. per cu. in.)	6.30	10.01	6.28	9.09	6.86	8.66	5.70	8.75	6.41	9.13
Work, total (inch-lbs. per cu. in.)	.....	.....	.....	.....	.....	.....	.....	.....	.....	12.50
IMPACT BENDING, 50-POUND HAMMER.										
Moisture (per cent) [1]	40.3	10.7	37.1	11.8	44.1	10.7	42.0	10.7	42.8	9.8
Specific gravity [2]	.397	.432	.396	.424	.346	.375	.370	.378	.372	.385
Fiber stress at elastic limit (lbs. per sq. in.)	.....	.....	9,654	11,843	7,300	11,420	7,870	11,880	7,840	9,780
Modulus of elasticity (1,000 lbs per sq. in.)	.....	.....	1,556	1,894	1,278	1,724	1,181	1,623	1,168	1,658
Work to elastic limit (inch-lbs. per cu. in.)	.....	.....	3.4	4.2	2.4	4.2	2.9	4.9	3.0	3.3
Inches drop 50-pound hammer to failure	23.7	32.0	24.7	25.4	27.5	26.6	26.7	24.3	28.3	24.2
COMPRESSION PARALLEL TO GRAIN.										
Moisture (per cent) [1]	40.9	11.3	38.2	12.3	43.8	12.2	40.1	9.6	40.8	10.7
Specific gravity [2]	.401	.427	.393	.427	.345	.370	.357	.378	.356	.384
Rings per inch	.....	.....	13.4	9.04	8.4	7.2	6.2	6.6	6.8	8
Summerwood (per cent)	.....	.....	44	38	42	32	35	38	38	34
Fiber stress at elastic limit (lbs. per sq. in.)	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Fiber stress at maximum load (lbs. per sq. in.)	2,875	5,973	2,840	6,234	2,390	4,240	2,410	6,060	2,380	5,920

[1] Per cent moisture based on oven-dry weight. [2] Specific gravity based on oven-dry weight and volume as tested.

The mechanical properties of all the groups of material for all conditions of seasoning are given in the single Table 1. An additional special table of data for comparing runs 147 and 148 is Table 9. These properties are average values of the average for all tests from each double bolt, or 8-foot log. For example: It has already been mentioned that kiln run 88 was made on material from three logs of shipment 504. They were the *a–b* and *i–j* bolts of tree 2 and bolt *e–f* of tree 3. The average property was determined for each bolt separately and the values given in the table are the averages of the bolt averages.

The four succeeding tables (Tables 2 to 5 inclusive) tabulate improvement ratios. They are obtained by different groupings of the data according to the points to be brought out. The first three of these tables (2, 3, and 4) pertain only to shipment 504, for which the air-dry tests completing the work have been made.

TABLE 2.—*Improvement ratio, Sitka spruce, air-dried and kiln-dried, with and without adjustment to 11 per cent moisture.*[1]

$$\text{Improvement ratio} = \frac{\text{Dry strength}}{\text{Green strength}}$$

Properties.	Air-dry shipment 325.		Shipment 504.													
			Air-dry to match kiln runs 88 and 89.		Kiln run 88.		Kiln run 89.		Air-dry to match kiln runs 91, 93, and 94.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.
STATIC BENDING.																
Fiber stress at elastic limit	2.39	2.09	1.93	2.10	2.24	2.00	1.98	1.95	1.78	1.93	1.80	1.78	1.90	1.91	2.26	2.05
Modulus of rupture	2.02	1.81	1.68	1.80	2.08	1.88	1.81	1.78	1.75	1.90	1.91	1.88	1.84	1.85	2.12	1.94
Modulus of elasticity	1.36	1.30	1.16	1.18	1.34	1.29	1.22	1.21	1.31	1.36	1.29	1.28	1.39	1.39	1.42	1.36
Work to maximum load	1.63	1.52	1.38	1.43	1.54	1.45	1.43	1.42	1.36	1.42	1.76	1.74	1.24	1.24	1.41	1.35
Total work	1.05	1.04	.....	.....	.85	.87	.78	.78	.....	.....	1.18	1.18	.....	.....	.....	.....
IMPACT BENDING, 50-POUND HAMMER.																
Fiber stress at elastic limit	1.76	1.62	1.26	1.32	1.44	1.37	1.36	1.39	1.29	1.33	1.35	1.34	1.39	1.38	1.58	1.49
Modulus of elasticity	1.35	1.29	1.24	1.30	1.30	1.25	1.25	1.27	1.34	1.38	1.36	1.35	1.39	1.38	1.55	1.46
Height of drop	1.21	1.18	1.07	1.08	1.14	1.12	1.05	1.05	1.03	1.03	1.21	1.21	1.11	1.11	1.32	1.27
COMPRESSION PARALLEL TO GRAIN.																
Fiber stress at elastic limit	.....	.....	.....	.....	2.70	2.37	2.44	2.35	.....	.....	2.35	2.25	.....	.....	.....	.....
Fiber stress at maximum load	2.22	1.97	2.12	2.37	2.50	2.22	2.32	2.24	2.07	2.37	2.34	2.25	2.47	2.61	2.92	2.38

[1] Fiber-saturation point=23 per cent. I. R.=Improvement ratio.

Table 2 presents ratios derived from the properties of material of shipments 325 and 504 as presented in Table 1. Ratios are given both with and without adjustment for moisture content. The next table (Table 3) was made up for the reason that the original data showed a consistent variation in the strength properties according as the test specimens came from near the central or the outer portions of the tree. It was thought that better comparisons between kiln-dried, green, and air-dried material would be had by using smaller units of matching—that is, by groups more inherently alike. Table 3 gives by inner and outer portions the properties of each bolt. ("Outer" and "inner" portions are divided by the circumferential splitting lines as illustrated in fig. 1 (E).) The improvement ratios included are based on average values of properties of bolts.

TABLE 3.—*Properties of Sitka spruce, shipment 504 (also improvement ratios with and without adjustment to 11 per cent moisture).*

SUMMARY OF INNER PORTION OF TREES ONLY.

Tree and bolt.	Seasoning.	Static bending.					Impact bending, 50-pound hammer.			Compression parallel to grain.			
		Number of tests.	Moisture.	M. of R.	M. of E.	Work.	Number of tests.	Moisture.	Ht. of drop.	Number of tests.	Moisture.	Sp. gr. test.	M. C. S.
			Per cent.	*Pounds per square inch.*	*1,000 pounds per square inch.*	*Inch-pounds per cubic inch.*		*Per cent.*	*Inches.*		*Per cent.*		*Pounds per square inch.*
2 a–b..	Green to match kiln runs 88 and 89.	17	.....	4,670	1,185	5.8	8	.....	26	35	.....	0.336	2,100
2 i–j...		14	.....	4,640	1,140	4.9	9	.....	18	28	.....	.326	2,050
3 e–f...		19	.....	5,370	1,270	5.3	8	.....	21	40	.....	.377	2,440
Average		.....	.....	4,890	1,198	5.3	.....	.....	21.7	.....	.....	.346	2,200
2 a–b..	Air dry to match kiln runs 88 and 89.	15	12.4	8,240	1,266	7.50	9	12.8	22.7	33	12.7	.367	4,590
2 i–j...		15	12.1	8,220	1,347	7.41	7	13.1	22.7	31	12.2	.358	4,740
3 e–f...		18	12.6	8,830	1,589	7.54	9	12.9	25.5	43	12.3	.411	4,890
Average		.....	12.4	8,430	1,401	7.48	.....	12.9	23.6	.....	12.4	.379	4,740
I. R. at test		.....	.....	1.72	1.17	1.41	.....	.....	1.09	.....	.....	.....	2.16
I. R.11		.....	.....	1.85	1.20	1.48	.....	.....	1.11	.....	.....	.....	2.39
2 a–b..	Kiln run 88...	6	9.5	10,100	1,585	8.1	5	9.7	27	11	9.5	.378	5,780
2 i–j...		3	9.8	9,730	1,515	8.5	4	9.5	25	8	9.0	.363	5,140
3 e–f...		6	7.6	10,890	1,650	8.7	8	7.8	26	12	7.8	.408	6.440
Average		.....	9.0	10,240	1,583	8.4	.....	9.0	26.0	.....	8.8	.383	5,790
I. R. at test		.....	.....	2.09	1.32	1.58	.....	.....	1.20	.....	.....	.....	2.63
I. R.11		.....	.....	1.89	1.27	1.48	.....	.....	1.17	.....	.....	.....	2.26
2 a–b..	Kiln run 89...	7	11.0	8,530	1,460	6.4	7	10.7	20	14	10.0	.308	5,460
2 i–j...		3	10.5	11,000	1,720	9.6	3	8.7	29	6	9.3	.361	5,500
3 e–f...		4	12.1	9,020	1,555	8.0	6	13.2	23	12	11.4	.401	5.180
Average		.....	11.2	9,520	1,578	8.0	.....	10.9	24.0	.....	10.2	.357	5,380
I. R. at test		.....	.....	1.95	1.32	1.51	.....	.....	1.11	.....	.....	.....	2.44
I. R.11		.....	.....	1.97	1.33	1.52	.....	.....	1.11	.....	.....	.....	2.31
1 c–d..	Green to match kiln runs 91, 93, and 94.	18	.....	4,710	1,130	4.5	8	.....	15	36	.....	.340	2,220
1 i–j...		18	.....	5,130	1,140	6.0	9	.....	19	39	.....	.341	2,210
4 e–f...		22	.....	4,620	1,094	5.6	5	.....	21	49	.....	.327	2,140
Average		.....	.....	4,820	1,121	5.4	.....	.....	18.3	.....	.....	.336	2,190
1 c–d..	Air dry to match kiln runs 91, 93, and 94.	19	12.0	8,220	1,450	7.85	8	11.8	13.8	38	12.8	.368	4,590
1 i–j...		23	12.1	9,030	1,503	8.22	8	11.4	22.8	41	12.6	.369	4,930
4 e–f...		23	12.3	8,180	1,414	7.58	9	13.0	21.1	46	12.8	.355	4,250
Average		.....	12.1	8,477	1,456	7.88	.....	12.1	19.2	.....	12.7	.364	4,590
I. R. at test		.....	.....	1.76	1.29	1.46	.....	.....	1.05	.....	.....	.....	2.09
I. R.11		.....	.....	1.86	1.32	1.52	.....	.....	1.06	.....	.....	.....	2.36
1 c–d..	Kiln run 91...	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1 i–j...		6	11.4	9,110	1,366	12.4	6	11.6	28	12	10.8	.370	5,410
4 e–f...		3	11.4	9,180	1,690	7.8	4	11.5	22	8	11.4	.366	5,470
Average		.....	11.4	9,140	1,528	10.1	.....	11.6	25	.....	11.1	.368	5,440
I. R. at test		.....	.....	1.90	1.36	1.87	.....	.....	1.36	.....	.....	.....	2.48
I. R.11		.....	.....	1.94	1.38	1.91	.....	.....	1.38	.....	.....	.....	2.50
1 c–d..	Kiln run 93...	4	11.2	7,780	1,620	5.2	3	10.2	21	8	12.0	.378	5,710
1 i–j...		2	12.4	9,480	1,552	7.5	2	11.0	24	4	12.8	.376	5,580
4 e–f...		2	10.0	9,610	1,450	8.8	2	9.6	24	4	10.3	.355	5,960
Average		.....	11.2	8,960	1,541	7.2	.....	10.3	23.0	.....	11.7	.370	5,750
I. R. at test		.....	.....	1.86	1.37	1.33	.....	.....	1.26	.....	.....	.....	2.63
I. R.11		.....	.....	1.88	1.38	1.34	.....	.....	1.24	.....	.....	.....	2.79
1 c–d..	Kiln run 94...	1	6.8	11,090	1,255	13.1	1	7.7	31	2	7.1	.379	7,620
1 i–j...		3	9.4	9,120	1,436	7.2	4	8.9	32	6	7.7	.377	7,170
4 e–f...		1	10.9	9,560	1,426	6.6	1	10.0	29	2	9.3	.374	5,760
Average		.....	9.0	9,920	1,372	9.0	.....	8.9	30.7	.....	8.0	.377	6,850
I. R. at test		.....	.....	2.06	1.22	1.67	.....	.....	1.68	.....	.....	.....	3.13
I. R.11		.....	.....	1.86	1.19	1.55	.....	.....	1.55	.....	.....	.....	2.49

TABLE 3.—*Properties of Sitka spruce, shipment 504 (also improvement ratios with and without adjustment to 11 per cent moisture*—Continued.

SUMMARY OF OUTER PORTION OF TREES ONLY.

Tree and bolt.	Seasoning.	Static bending.					Impact bending, 50-pound hammer.			Compression parallel to grain.			
		Number of tests.	Moisture.	M. of R.	M. of E.	Work.	Number of tests.	Moisture.	Ht. of drop.	Number of tests.	Moisture.	Sp. gr. test.	M. C. S.
			Per cent.	*Pounds per square inch.*	*1,000 pounds per square inch.*	*Inch-pounds per cubic inch.*		*Per cent.*	*Inches.*		*Per cent.*		*Pounds per square inch.*
2 a–b..	Green to match kiln runs 88 and 89.	23	.....	5,360	1,285	5.7	8	.....	23	36	.....	0.347	2,380
2 i–j...		19	.....	5,250	1,139	5.8	7	.....	20	29	.....	.337	2,300
3 e–f...		22	.....	4,750	974	5.0	5	.....	19	43	.....	.335	1,970
Average		.....	.....	5,120	1,133	5.5	.....	.....	20.7	.....	.....	.340	2,217
2 a–b..	Air dry to match kiln runs 91, 93, and 94.	20	12.1	8,854	1,381	8.02	7	12.7	24	28	12.6	.380	4,860
2 i–j...		19	12.0	8,550	1,374	8.01	9	12.5	21.5	27	12.3	.364	4,850
3 e–f...		21	12.5	8,050	1,166	6.13	6	13.2	17.7	36	13.0	.365	4,130
Average		.....	12.2	8,485	1,307	7.39	.....	12.8	21.1	.....	12.6	.370	4,613
I. R. at test		.....	.....	1.66	1.15	1.34	.....	.....	1.02	.....	.....	.....	2.08
I. R.$_{11}$		.....	.....	1.76	1.17	1.38	.....	.....	1.02	.....	.....	.....	2.33
2 a–b..	Kiln run 88...	19	9.9	10,580	1,565	8.7	20	9.8	24	37	10.3	.388	5,480
2 i–j...		9	8.7	11,620	1,706	9.5	9	8.9	26	19	9.0	.375	5,740
3 e–f...		17	8.8	9,230	1,344	6.5	18	8.8	20	39	8.7	.369	5,170
Average		.....	9.1	10,480	1,538	8.2	.....	9.2	23.3	.....	9.3	.377	5,460
I. R. at test		.....	.....	2.05	1.36	1.49	.....	.....	1.12	.....	.....	.....	2.46
I. R.$_{11}$		.....	.....	1.86	1.30	1.41	.....	.....	1.10	.....	.....	.....	2.20
2 a–b..	Kiln run 89...	16	11.8	9,520	1,442	8.4	16	12.1	22	31	10.2	.386	5,560
2 i–j...		15	8.8	10,400	1,523	8.9	13	9.2	23	30	9.1	.358	5,630
3 e–f...		17	13.9	7,270	1,177	5.8	16	14.8	17	37	12.6	.360	4,090
Average		.....	11.5	9,060	1,382	7.7	.....	12.0	20.7	.....	10.6	.368	5,090
I. R. at test		.....	.....	1.77	1.22	1.40	.....	.....	1.00	.....	.....	.....	2.29
I. R.$_{11}$		.....	.....	1.81	1.23	1.42	.....	.....	1.00	.....	.....	.....	2.23
1 c–d..	Green to match kiln runs 91, 93, 94.	17	.....	4,700	945	5.2	7	.....	18	35	.....	.334	2,180
1 i–j...		18	.....	4,920	1,095	5.2	7	.....	17	32	.....	.333	2,230
4 e–f...		26	.....	4,830	990	5.8	11	.....	21	45	.....	.345	2,180
Average		.....	.....	4,820	1,010	5.4	.....	.....	18.7	.....	.....	.337	2,200
1 c–d..	Air dry to match kiln runs 91, 93, and 94.	16	12.6	8,440	1,441	7.10	7	12.1	20.0	29	12.8	.362	4,520
1 i–j...		16	12.2	8,500	1,387	7.72	8	12.1	21.5	32	12.9	.360	4,640
4 e–f...		29	12.9	8,110	1,199	6.84	5	12.6	17.2	41	13.3	.365	4,200
Average		.....	12.6	8,350	1,342	7.22	.....	12.3	19.6	.....	13.0	.362	4,453
I. R. at test	93 and 94	.....	.....	1.73	1.33	1.33	.....	.....	1.05	.....	.....	.....	2.02
I. R.$_{11}$		.....	.....	1.88	1.39	1.39	.....	.....	1.06	.....	.....	.....	2.33
1 c–d..	Kiln run 91...	12	10.9	9,800	1,425	11.6	11	11.1	23	25	10.3	.352	5,190
1 i–j...		8	9.6	9,620	1,315	8.9	8	8.5	21	16	9.3	.355	5,110
4 e–f...		14	12.0	8,300	1,288	6.1	11	11.6	19	31	10.7	.367	4,810
Average		.....	10.8	9,240	1,343	8.9	.....	10.4	21.0	.....	10.1	.360	5,040
I. R. at test		.....	.....	1.92	1.33	1.65	.....	.....	1.12	.....	.....	.....	2.29
I. R.$_{11}$		.....	.....	1.90	1.33	1.64	.....	.....	1.11	.....	.....	.....	2.16
1 c–d..	Kiln run 93...	4	10.2	8,930	1,458	6.6	4	10.6	20	8	12.0	.350	5,040
1 i–j...		6	11.8	9,210	1,600	7.4	6	11.2	25	10	11.7	.363	5,710
4 e–f...		6	11.1	8,840	1,265	6.2	5	10.5	17	11	11.4	.360	4,770
Average		.....	11.0	8,990	1,441	6.7	.....	10.8	20.7	.....	11.7	.358	5,170
I. R. at test		.....	.....	1.86	1.43	1.24	.....	.....	1.11	.....	.....	.....	2.35
I. R.$_{11}$		.....	.....	1.86	1.43	1.24	.....	.....	1.11	.....	.....	.....	2.48
1 c–d..	Kiln run 94...	6	9.5	10,020	1,530	7.3	9	9.2	24	18	7.8	.366	6,200
1 i–j...		6	9.8	10,800	1,720	8.1	5	9.7	28	12	9.0	.379	6,880
4 e–f...		8	9.4	10,280	1,435	6.9	8	9.1	21	18	8.3	.374	5,910
Average		.....	9.6	10,370	1,562	7.4	.....	9.3	24.3	.....	8.4	.373	6,330
I. R. at test		.....	.....	2.15	1.55	1.37	.....	.....	1.30	.....	.....	.....	2.88
I. R.$_{11}$		.....	.....	1.99	1.48	1.33	.....	.....	1.26	.....	.....	.....	2.39

Explanation of terms, etc.:
Moisture content based on oven-dry weight
M. of R.=Modulus of rupture—pounds per square inch.
M. of E.=Modulus of elasticity—1,000 pounds per square inch.
Wk.=Work to maximum load—inch-pounds per cubic inch.
M. C. S.=Maximum crushing strength—pounds per square inch.
Ht. of drop=Height of drop of 50-pound hammer to complete failure—inches.
I. R.=Improvement ratio=$\frac{\text{dry strength}}{\text{green strength}}$.
I. R.$_{11}$=Improvement ratio—adjusted to 11 per cent moisture.
Sp. gr. test=Specific gravity based on oven-dry weight and volume as tested.

Improvement ratios based on a still further subdivision of the unit for matching are shown in Table 4. These are derived from some of the values shown in the preceding table. Only the extreme lower and upper bolts from among those available are included, so that the trees 2 and 3, having only the bolts *e–f*, are not represented. Tables 3 and 4 serve the purpose of detecting differences, if any exist, between the effect of drying on material from different parts of the trees, and are useful in supporting the conclusions reached from the study of ratios based on the general properties shown in Table 2.

TABLE 4.—*Summary of improvement ratios according to bolts—Sitka spruce—shipment 504. Kiln runs 88, 89, 91, 93, and 94 and air dry to match.*

Property.	Seasoning.	Tree No.	Bolts.	Inner portion.				Outer portion.			
				Lower bolt, A–B or C–D.		Upper bolt, I–J.		Lower bolt, A–B or C–D.		Upper bolt, I–J.	
				I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.
				1	2	3	4	5	6	7	8
M. of R.	Air dry to match kiln runs 88 and 89.	2	A–B, I–J	1.76	1.90	1.77	1.87	1.65	1.74	1.63	1.71
	Kiln run 88	2	A–B, I–J	2.16	1.98	2.09	1.96	1.97	1.86	2.22	1.95
	Kiln run 89	2	A–B, I–J	1.82	1.82	2.37	2.29	1.78	1.86	1.98	1.78
	Air dry to match kiln runs 91, 93, and 94.	1	C–D, I–J	1.74	1.83	1.76	1.86	1.80	1.97	1.73	1.84
	Kiln run 91	1	C–D, I–J					2.08	2.07	1.95	1.82
	Kiln run 93	1	C–D, I–J	1.65	1.67	1.85	2.00	1.90	1.83	1.87	1.96
	Kiln run 94	1	C–D, I–J	2.35	1.86	1.78	1.66	2.14	1.97	2.19	2.04
M. of E.	Air dry to match kiln runs 88 and 89.	2	A–B, I–J	1.07	1.08	1.18	1.20	1.08	1.09	1.21	1.23
	Kiln run 88	2	A–B, I–J	1.34	1.30	1.33	1.30	1.22	1.20	1.50	1.41
	Kiln run 89	2	A–B, I–J	1.23	1.23	1.51	1.48	1.12	1.11	1.34	1.28
	Air dry to match kiln runs 91, 93, and 94.	1	C–D, I–J	1.28	1.31	1.32	1.36	1.52	1.62	1.27	1.30
	Kiln run 91	1	C–D, I–J					1.51	1.51	1.20	1.18
	Kiln run 93	1	C–D, I–J	1.43	1.44	1.36	1.42	1.54	1.50	1.46	1.50
	Kiln run 94	1	C–D, I–J	1.11	1.08	1.26	1.23	1.62	1.54	1.57	1.51
Work	Air dry to match kiln runs 88 and 89.	2	A–B, I–J	1.29	1.34	1.51	1.57	1.41	1.46	1.38	1.42
	Kiln run 88	2	A–B, I–J	1.40	1.35	1.73	1.65	1.53	1.48	1.64	1.52
	Kiln run 89	2	A–B, I–J	1.10	1.10	1.96	1.91	1.47	1.51	1.53	1.41
	Air dry to match kiln runs 91, 93, and 94.	1	C–D, I–J	1.74	1.83	1.37	1.41	1.36	1.43	1.48	1.55
	Kiln run 91	1	C–D, I–J					2.23	2.22	1.71	1.62
	Kiln run 93	1	C–D, I–J	1.15	1.15	1.25	1.29	1.27	1.25	1.42	1.46
	Kiln run 94	1	C–D, I–J	2.91	2.20	1.20	1.17	1.40	1.35	1.56	1.50
M. C. S.	Air dry to match kiln runs 88 and 89.	2	A–B, I–J	2.19	2.48	2.31	2.54	2.04	2.28	2.11	2.31
	Kiln run 88	2	A–B, I–J	2.75	2.46	2.50	2.19	2.30	2.20	2.49	2.18
	Kiln run 89	2	A–B, I–J	2.60	2.42	2.68	2.37	2.34	2.22	2.45	2.17
	Air dry to match kiln runs 91, 93, and 94.	1	C–D, I–J	2.06	2.34	2.23	2.52	2.07	2.35	2.08	2.39
	Kiln run 91	1	C–D, I–J					2.38	2.29	2.30	2.07
	Kiln run 93	1	C–D, I–J	2.57	2.80	2.52	2.97	2.31	2.49	2.36	2.71
	Kiln run 94	1	C–D, I–J	3.42	2.53	3.24	2.52	2.84	2.28	3.08	2.62
Ht. of drop	Air dry to match kiln runs 88 and 89.	2	A–B, I–J	.87	.85	1.26	1.32	1.04	1.05	1.07	1.08
	Kiln run 88	2	A–B, I–J	1.038	1.03	1.39	1.34	1.04	1.04	1.30	1.25
	Kiln run 89	2	A–B, I–J	.77	.78	1.61	1.49	.96	.96	1.15	1.13
	Air dry to match kiln runs 91, 93, and 94.	1	C–D, I–J	.92	.92	1.20	1.21	1.11	1.12	1.25	1.28
	Kiln run 91	1	C–D, I–J					1.28	1.28	1.24	1.20
	Kiln run 93	1	C–D, I–J	1.40	1.37	1.26	1.26	1.11	1.11	1.47	1.48
	Kiln run 94	1	C–D, I–J	2.06	1.76	1.68	1.56	1.33	1.28	1.64	1.56

Explanation of terms:
M. of R.=Modulus of rupture, static bending.
M. of E.=Modulus of elasticity, static bending.
Work=Work to maximum load, static bending.
M. C. S.=Maximum crushing strength, compression parallel to grain.
Ht. of drop=Height of drop, impact bending.
I. R.=Improvement ratio.
Improvement ratios adjusted to 11 per cent moisture.
Fiber-saturation point=23 per cent.

The improvement ratios for material from shipments 563 and 578 (Table 5), for which the air-dried material is not yet ready for test, are obtained in a somewhat different manner. The ratios are computed for individual double bolts, but without subdivision into inner and outer portions for each kiln run. The averages for the ratios for the several bolts are then regarded as the improvement ratios corresponding to the kiln run. The ratios were so derived for kiln runs 147, 148, 163, 171, and 172, and are shown in Table 5.

TABLE 5.—*Improvement ratios according to bolts (adjusted to 11 per cent moisture).*

[Sitka spruce: Kiln runs 147 and 148, shipment 563, and kiln runs 163, 171, and 172, shipment 578.]

Seasoning.	Tree and bolt.	Static bending.						Impact bending, 50-pound hammer.			Compression parallel to grain.		
			M. of R.		M. of E.		Work to maximum load.		Height of drop.			Max. cr. strength.	
		Moisture.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	Moisture.	I. R. as tested.	I. R. adjusted.	Moisture.	I. R. as tested.	I. R. adjusted
		Per ct.							*Per ct.*			*Per ct.*		
Kiln run 147 (ship. 563).	1 a–b	11.6	1.85	1.91	1.40	1.43	1.84	1.90	12.7	1.21	1.25	12.5	2.10	2.34
	1 c–d	11.2	1.87	1.89	1.01	1.01	.....	.....	10.5	1.36	1.35	11.1	2.07	2.08
	2 a–b	10.5	1.65	1.62	.76	.77	1.52	1.49	10.0	1.46	1.42	10.8	2.01	1.99
	2 c–d	10.2	1.78	1.72	.93	.93	.....	.....	9.7	1.55	1.49	11.5	2.19	2.27
	5 c–d	9.9	1.85	1.76	1.26	1.24	1.30	1.27	10.4	1.25	1.24	10.5	1.93	1.88
Average		.....	1.80	1.78	1.07	1.07	1.55	1.53	.....	1.37	1.36	.....	2.06	2.10
Kiln run 148 (ship. 563).	1 a–b	12.6	1.64	1.77	1.16	1.19	1.55	1.66	13.1	.89	.87	13.8	1.95	2.39
	1 c–d	11.1	1.75	1.75	1.10	1.10	1.71	1.72	11.0	1.05	1.05	12.7	2.09	2.36
	2 a–b	10.1	1.94	1.85	1.29	1.27	1.29	1.27	11.5	1.19	1.20	11.0	2.42	2.42
	2 c–d	9.7	2.04	1.90	1.24	1.22	1.50	1.44	11.2	1.19	1.19	12.3	2.49	2.79
	5 c–d	10.9	1.64	1.64	.93	.93	1.17	1.17	12.0	.85	.84	11.8	2.03	2.13
Average		.....	1.80	1.78	1.14	1.14	1.44	1.45	.....	1.03	1.03	.....	2.20	2.42
Kiln run 163 (ship. 578).	2 c–d	12.8	1.76	1.95	1.14	1.17	1.34	1.41	10.0	.94	.94	12.9	1.81	2.02
	3 e–f	12.4	1.61	1.71	1.15	1.17	1.17	1.19	11.4	1.00	1.00	11.5	1.74	1.78
Average		.....	1.68	1.82	1.14	1.16	1.25	1.29	.....	.97	.97	.....	1.77	1.89
Kiln run 171 (ship. 578).	1 a–b	10.6	2.06	2.01	1.17	1.16	1.65	1.63	10.7	.85	.85	10.0	2.41	2.25
	4 a–b	10.6	1.93	1.89	1.39	1.37	1.44	1.42	13.0	.84	.81	10.0	2.67	2.47
	5 a–b	9.2	2.10	1.91	1.34	1.29	1.42	1.36	9.4	.84	.86	9.0	2.46	2.16
	6 a–b	9.1	2.12	1.91	1.44	1.37	1.67	1.56	9.7	1.19	1.17	9.2	2.54	2.25
Average		.....	2.05	1.93	1.33	1.30	1.54	1.49	.....	93	.93	.....	2.52	2.27
Kiln run 172 (ship. 578).	1 a–b	9.9	2.08	1.96	1.29	1.27	1.29	1.27	9.7	.82	.84	11.7	2.36	2.49
	4 a–b	10.0	2.04	1.93	1.25	1.23	1.43	1.39	8.5	.83	.86	10.6	2.41	2.35
	5 a–b	10.3	2.08	2.00	1.40	1.37	1.48	1.45	10.8	.70	.70	10.2	2.49	2.35
	6 a–b	12.1	2.03	2.18	1.35	1.39	1.53	1.60	10.2	1.19	1.18	10.1	2.66	2.48
Average		.....	2.06	2.0	1.32	1.31	1.43	1.41	.....	.89	.90	.....	2.48	2.41

M. of R.=Modulus of rupture.
M. of E.=Modulus of elasticity.
Max. cr. strength=Maximum crushing strength.
I. R.=Improvement ratio.
Fiber-saturation point=23 per cent.

The improvement ratios as given in Tables 2, 3, 4, 5, and 10 are put into graphical form in figures 8, 9, and 10. Figure 8 also shows ratios for air seasoning of a closely allied species, red spruce, based on data from a bulletin of the Forest Service.[1] In figure 8 the values plotted for previous air-dry tests of shipment 325 and the values of improvement ratios shown by dotted lines (shipment 504, kiln runs 88, 89, 91, 93, 94) are from Table 2. The last five ratios under each property are the average values taken from Table 5. Ratios from Table 3 are also graphed in this figure.

The ratios of Table 4 are plotted in figure 9. Figure 10 shows the ratios, by individual bolts, for runs 147 and 148, from Table 10. This figure is included because of the bearing of these ratios on the question of the effect of high temperature.

DISCUSSION.

COMPARISON OF KILN-DRIED WITH MATCHED AIR-DRIED MATERIAL.

The outstanding fact indicated by figure 9 and by that part of figure 8 pertaining to material for which air-dry tests are available (shipment 504) is the very general excellence of the material which has been kiln dried, as compared in each case with the corresponding air-dried stock. Irrespective of the unit of matching, whether matched by units of three whole bolts, by the inner and outer portions for three bolts, or by inner and outer portions for individual bolts,

[1] Forest Service Bulletin 70, The Effect of Moisture on the Strength and Stiffness of Wood.

the excellence of the kiln-dried material is general with respect to all of the five properties.

The conclusions as to the relative merits of the various kiln runs are:

(1) Of the two runs 88 and 89 made on the same group of material, 89 is the poorer, although it is better than the corresponding air-dry except in compression parallel, and possibly also in height of drop.

(2) In the other group of material (including runs 91, 93, and 94) kiln run 94 shows, with most consistency, the highest improvement ratio. Taking all the properties into consideration, it is difficult to choose between runs 91 and 93. If, however, we base a decision on the highly important properties of work to maximum load and height of drop, it would be concluded that run 91 is the better, in spite of the higher temperature used throughout the run.

It will be noticed that the air-dried material of the group matching runs 88 and 89 shows about the same improvement over green as does that of the group matching runs 91, 93, and 94, and that they differ considerably less from each other than they do from the air-dry of the previous shipment, 325. The property which is an exception to this statement is the very variable and less important one of modulus of elasticity. This brings out the point that, while the relative suitability of the several kiln runs can be determined by intercomparison of the improvement ratios, it is not possible to state positively that any of them give improvements equal or superior to those to be obtained by air drying until *matched* air-dried material has actually been tested. To illustrate: If tests on the air-dried groups matching kiln runs 88, 89, 91, 93, and 94 were not available, and judgment of these runs had to be based on a comparison of their improvement ratios with those of the previously tested air-dry of shipment 325, and without any allowance for variability, the conclusion would be reached that of these runs 94 alone had yielded stock equal or superior to air-dry. It is now evident that such a comparison would be misleading. It so happens that in this instance this method of comparison is safe, in that it does not give a false idea concerning the safety of kiln-drying. On the other hand, it might happen that such a comparison would lead to the conclusion that a given drying process was entirely safe, when such was not the case. However, in making such comparisons careful consideration must be given to the variations to be expected. This was done in the first analysis of the effect of runs 88, 89, 91, 93, and 94, and the conclusion was reached that, with the possible exception of run 89, all had given satisfactory results. That all the runs, 89 included, have given satisfactory results is indicated by the data presented herein.

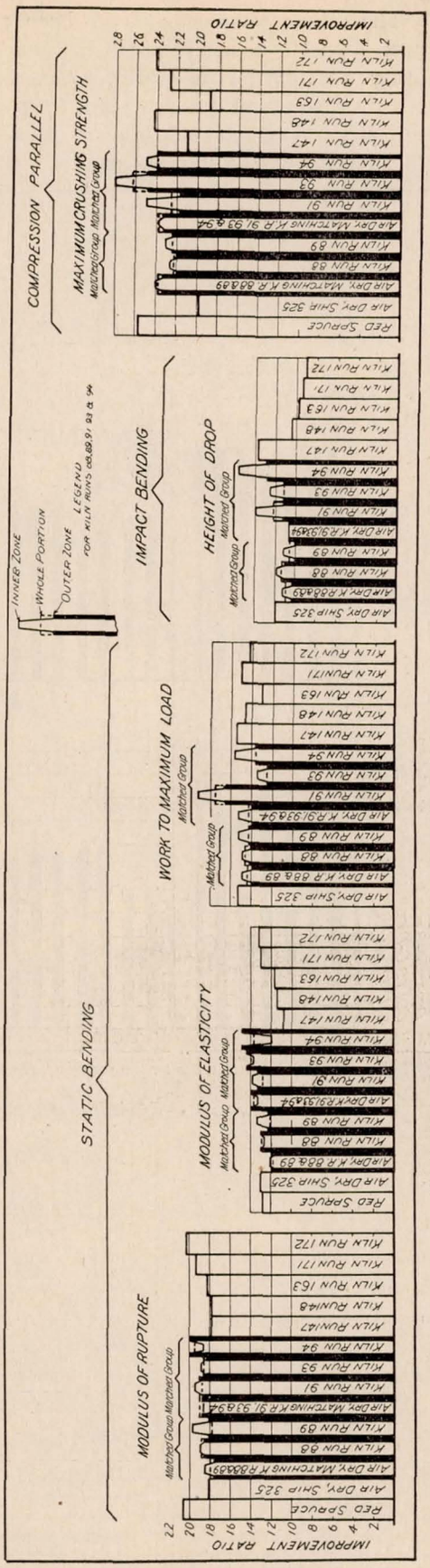


FIG. 8.—Improvement ratios for comparison of ten groups of kiln-dried and three of air-dried stock, Sitka spruce.

The above conclusions have been arrived at by a consideration of the ratios shown in figures 8 and 9, mentally balancing a deficiency in one property against superior excellence in another. While it is necessary to exercise care in any attempt to reduce comparisons to an exact mathematical basis, it is interesting to note how comparisons on such a basis lead to practically the same conclusions as given. Table 6[1] gives the results of a computation of the "efficiencies" of the various runs.

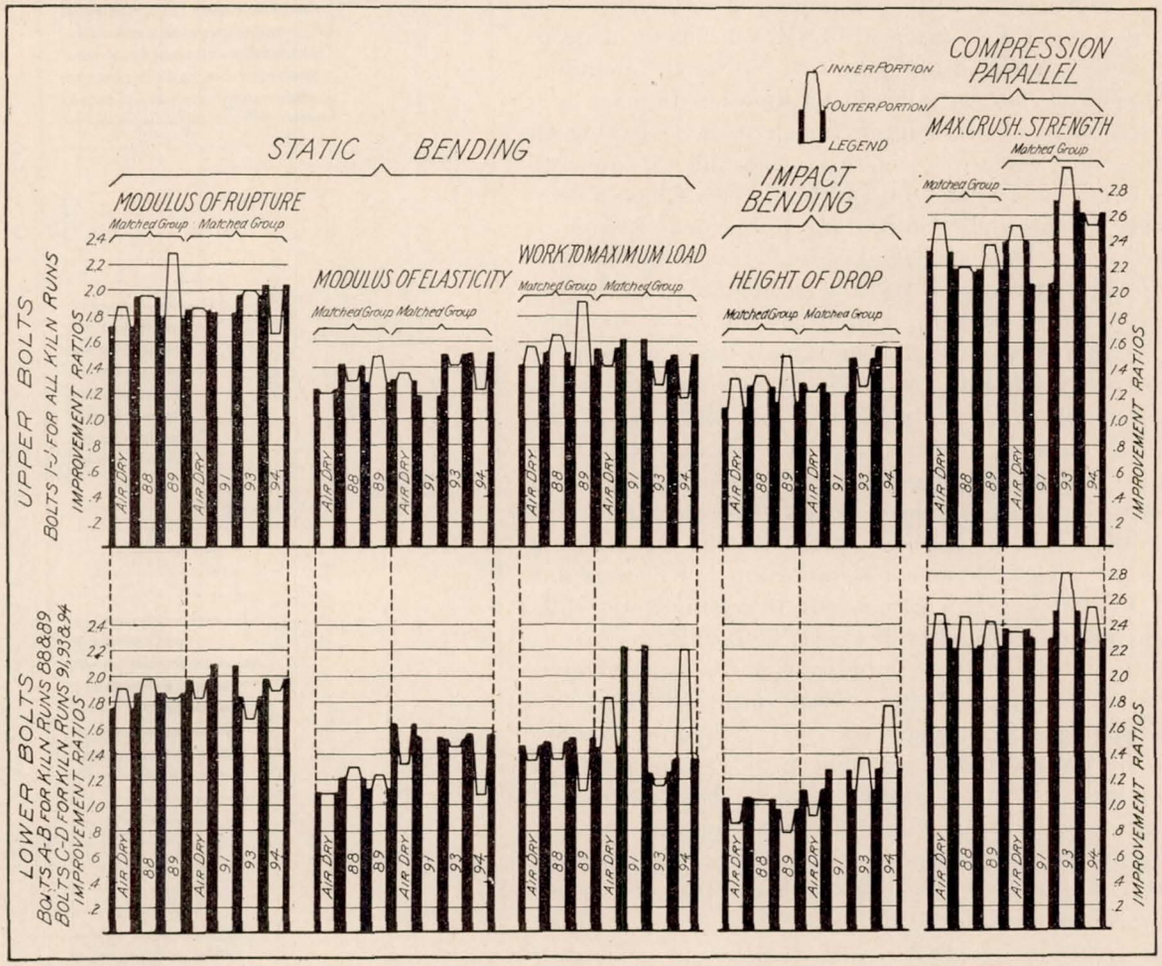


FIG. 9.—Improvement ratios for comparing upper and lower bolts and inner and outer portions, Sitka spruce, shipment 504.

TABLE 6.—*Efficiencies of various kiln runs—Sitka spruce—Shipment 504.*

Property.	F	Kiln run 88.		Kiln run 89.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	104.3	208.6	98.9	197.8	98.9	197.8	97.4	194.8	102.3	204.2
Modulus of elasticity	4	109.0	436.0	102.5	410.0	94.1	376.4	102.3	409.2	100.0	400.0
Work to maximum load	3	102.2	306.6	99.3	297.9	122.6	367.8	87.4	262.2	95.0	285.0
Drop	3	103.8	311.4	97.3	291.9	114.1	342.3	104.8	314.4	119.9	359.7
Maximum crushing strength	2	93.7	187.4	94.5	189.0	95.0	190.0	110.5	221.0	100.5	201.0
ΣE	....	513.0	.....	492.5	.....	524.7	.....	502.4	.....	517.7	.....
ΣE÷5=Average E	....	102.6	.....	98.5	.....	104.9	.....	100.5	.....	103.5	.....
Σ(E×F)	....	.....	1,450.0	.....	1,376.6	.....	1,474.3	.....	1,401.6	.....	1,449.9
Σ(E×F)÷ΣF=Weighted average E	....	.....	103.6	.....	98.3	.....	105.3	.....	100.1	.....	103.6

F=Weighting factor.

$$E=\text{Efficiency}=\frac{\text{Improvement ratio for property of kiln-dry}}{\text{Improvement ratio for same property of corresponding air-dry}}$$

[1] The weighting factors *F* used in this and other tables are those which have been used in computing a composite figure to measure the suitability of various species for aircraft use. The relative importance of the various properties and the applicability of such factors in the present instance might be subject to some question. However, the facts that the "average efficiencies" and "weighted average efficiencies" as given in Table 6 do not differ significantly, and that both methods put the various kiln runs in the same order, indicates that, in the present instance at least, any reasonable weighting scheme would bring approximately the same results.

Table 6 is derived from figure 8 and with its footnotes is self-explanatory. The arrangement of kiln runs in order of descending weighted average efficiencies as obtained from Table 6 is as follows:

	Efficiency (per cent).
Air drying	100.0
Kiln run 91	105.3
Kiln run 88	103.6
Kiln run 94	103.6
Kiln run 93	100.1
Kiln run 89	98.3

Comparison with figure 3 shows that the above list puts the kiln runs approximately in descending order with respect to temperatures. It is also notable that, measured by this method, all runs except 89 gave results superior to air drying.

TABLE 7.—*Efficiencies of various kiln runs—Sitka spruce—Shipment 504—Upper bolts.*

(A)—OUTER PORTION.

Property.	F	Kiln run 88.		Kiln run 89.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	113.4	226.8	104.0	208.0	98.9	197.8	106.5	213.0	113.0	226.0
Modulus of elasticity	4	115.3	461.2	104.0	416.0	90.8	363.2	115.2	460.8	116.9	467.6
Work	3	107.0	321.0	99.3	297.9	104.8	314.4	94.1	282.3	96.9	290.7
Drop	3	116.0	348.0	104.5	313.5	93.5	280.5	115.8	347.4	121.6	364.8
Compression	2	94.2	188.4	94.0	188.0	86.6	173.2	113.5	227.0	109.7	219.4
Σ(E×F)	....	.....	1,545.4	.....	1,423.4	.....	1,329.1	.....	1,530.5	.....	1,568.5
Σ(E×F)÷ΣF=weighted average E	....	.....	110.4	.....	101.7	.....	94.9	.....	109.3	.....	112.0

(B)—INNER PORTION.

Property.	F	Kiln run 88.		Kiln run 89.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	104.9	209.8	122.3	244.6	.....	.....	107.5	215.0	89.2	178.4
Modulus of elasticity	4	108.2	432.8	124.0	496.0	.....	.....	104.3	417.2	90.5	362.0
Work	3	105.9	317.7	121.6	364.8	.....	.....	89.5	268.5	82.4	247.2
Drop	3	101.5	304.5	113.0	339.0	.....	.....	105.0	315.0	128.0	384.0
Compression	2	86.2	172.4	93.4	186.8	.....	.....	118.0	236.0	100.0	200.0
Σ(E×F)	....	.....	1,437.2	.....	1,631.2	.....	.....	.....	1,451.7	.....	1,371.6
Σ(E×F)÷ΣF=weighted average E	....	.....	102.7	.....	116.5	.....	.....	.....	103.7	.....	97.9

F=Weighting factor

$$E=\text{Efficiency}=\frac{\text{Improvement ratio for property of kiln dry}}{\text{Improvement ratio for same property of corresponding air dry}}$$

TABLE 8.—*Efficiencies of kiln runs—Sitka spruce—Shipment 504—Lower bolts.*

(A)—OUTER PORTION.

Property.	F	Kiln run 88.		Kiln run 89.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	106.9	213.8	106.9	213.8	105.0	210.0	92.9	185.8	100.0	200.0
Modulus of elasticity	4	110.0	440.0	101.9	407.6	93.8	375.2	92.5	370.0	95.0	380.0
Work	3	101.2	303.6	103.3	309.9	155.0	465.0	87.4	262.2	94.4	283.2
Drop	3	98.1	294.3	90.6	271.8	114.2	342.6	100.0	300.0	114.2	342.6
Compression	2	96.5	193.0	97.4	194.8	92.6	185.2	105.5	211.0	96.5	193.0
Σ(E×F)	....	.....	1,444.7	.....	1,397.9	.....	1,578.0	.....	1,329.0	.....	1,398.8
Σ(E×F)÷ΣF=weighted average E	....	.....	103.2	.....	99.7	.....	112.7	.....	94.7	.....	99.0

(B)—INNER PORTION.

Property.	F	Kiln run 88.		Kiln run 89.		Kiln run 91.		Kiln run 93.		Kiln run 94.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	104.1	208.2	95.7	191.4	.....	.....	91.1	182.2	103.1	206.2
Modulus of elasticity	4	120.2	480.8	114.9	459.6	.....	.....	119.0	476.0	88.5	354.0
Work	3	100.9	302.7	82.0	246.0	.....	.....	62.8	188.4	120.1	360.3
Drop—impact	3	121.0	363.0	91.7	275.1	.....	.....	148.9	446.7	191.2	573.6
Compression	2	99.1	198.2	97.5	195.0	.....	.....	119.7	239.4	108.0	216.0
Σ(E×F)	....	.....	1,552.9	.....	1,367.1	.....	.....	.....	1,532.7	.....	1,710.1
Σ(E×F)÷ΣF=weighted average E	....	.....	111.0	.....	97.5	.....	.....	.....	109.5	.....	122.1

F=Weighting factor

$$E=\text{Efficiency}=\frac{\text{Improvement ratio for property of kiln dry}}{\text{Improvement ratio for same property of corresponding air dry}}$$

Tables 7 and 8 present data similar to those of Table 6, but derived from figure 9. They show efficiency figures for various smaller groups of material. Tables 7 and 8, as would be expected, disclose considerably greater variations than are shown in Table 6. The averages naturally show variations from those of Table 6. In no case, however, is the drop of these averages below 100 per cent serious. Some rather low "efficiencies" for individual properties are found among these figures for smaller groups of material. It is notable, however, that there are few cases in which both work to maximum load and drop, or both modulus of rupture and maximum crushing strength, fall low. It is doubtful also whether such variations as are found in these tables can be supposed to be the result of the kiln processes. It is more probable that they result from actual inherent differences between the kiln-dried and air-dried material. Such differences are more likely to occur between small groups than between large ones. In other words, the differences between small groups of tests are likely to have little meaning, and conclusions as to the effect of the kiln processes can best be reached from consideration of the larger groups.

Table 6, then, leads to the following conclusions, which are practically the same as those previously stated:

1. Runs 88, 91, 93, and 94 have produced material equal or superior to material that was air-dried.

2. Run 89 is probably the poorest of the runs, but may be considered practically equal to the air-dry.

From Nos. 1 and 2 would follow:

3. Within the limits used, 115° to 180° F., the strength properties of Sitka spruce are independent of the temperature of drying (but see following paragraph).

As has been mentioned, it is to be expected that a given process or set of drying conditions will have a different effect on different groups of material from the same species, and that it may be possible for a process to be safe for one group and very damaging to another. This expectation has been fulfilled in this series of tests, and consideration of some of the runs yet to be discussed necessitates a considerable modification of conclusion No. 3 above.

DISCUSSION OF RUNS FOR WHICH DATA ON MATCHED AIR-DRIED MATERIAL ARE NOT YET AVAILABLE.

Consideration is now to be given to material from additional kiln runs. Air-dried material matched to that dried in these runs and tested is not yet available for test.

Runs 147 and 148.—Two of these runs (147 and 148) are particularly worthy of attention.

Run 147 was made on pieces 2¼ by 2¼ inches in section, by 4 feet long. The temperature was 130° F. at the beginning and 150° F. at the end. The humidity and steaming treatments were so regulated as to keep casehardening at a minimum. Run 148 was on material from the same logs as run 147; material was in the form of wide planks 2½ inches thick and the temperatures were 160° F. initial and 180° F. final.

Strength data for these runs are given in Tables 1 and 9. Improvement ratios are shown in Table 5 and in figure 8. These improvement ratios are based on all the material in each run as compared to corresponding green material, and serve for a general comparison of these two with other runs.

TABLE 9.—*Mechanical properties of Sitka spruce.*

[Special table for comparing kiln runs 147 and 148, shipment 563.]

Kiln runs.	Tree and bolt.	Static bending.									
		Moisture.[1]		Specific gravity.[2]		Modulus of *rupture.*		Modulus of *elasticity.*		Work to maximum load.	
		Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.
		Per cent.	*Per cent.*			*Pounds per square inch.*	*Pounds per square inch.*	*1,000 pounds per square inch.*	*1,000 pounds per square inch.*	*Inch-pounds per cubic inch.*	*Inch-pounds per cubic inch.*
147	1 c–d	11.2	40.0	0.446	0.423	11,900	6,370	1,760	1,745	.....	.....
	2 a–b	10.5	36.4	.404	.382	9,460	5,728	1,323	1,738	7.4	4.90
	2 c–d	10.2	32.2	.410	.392	10,000	5,630	1,302	1,398	.....	.....
	5 c–d	9.9	37.4	.390	.365	9,930	5,355	1,436	1,135	7.7	5.90
Average		10.4	36.5	.412	.391	10,322	5,771	1,455	1,504	7.6	5.40
148 (outer portion)	1 c–d	12.3	36.0	.445	.411	10,914	6,579	1,671	1,604	.....	.....
	2 a–b	9.8	32.4	.409	.389	11,360	5,980	1,803	1,405	8.6	6.49
	2 c–d	10.0	51.2	.418	.352	11,741	5,709	1,677	1,358	.....	.....
	5 c–d	11.5	34.3	.375	.359	9,300	5,904	1,220	1,392	6.9	6.23
Average		10.9	38.5	.412	.378	10,829	6,043	1,593	1,440	7.8	6.36

Kiln runs.	Tree and bolt.	Impact bending, 50-pound hammer.						Compression parallel to grain.					
		Moisture.[1]		Specific gravity.[2]		Height of drop.		Moisture.[1]		Specific gravity.[2]		Maximum crushing strength.	
		Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.	Kiln run 147 or 148.	Green.
		Per cent.	*Per cent.*			*Inches.*	*Inches.*	*Per cent.*	*Per cent.*			*Pounds per square inch.*	*Pounds per square inch.*
147	1 c–d	10.5	40.2	0.445	0.410	38.0	28.0	11.1	39.0	0.430	0.408	6,515	3,138
	2 a–b	10.0	35.0	.421	.377	28.0	19.2	10.8	37.2	.410	.384	5,270	2,622
	2 c–d	9.7	32.8	.421	.384	31.0	20.0	11.5	34.0	.415	.389	6,230	2,845
	5 c–d	10.4	36.2	.390	.368	25.5	20.4	10.5	37.5	.394	.364	5,490	2,850
Average		10.1	36.1	.419	.385	30.6	21.9	10.9	36.9	.412	.386	5,876	2,864
148 (outer portion)	1 c–d	11.2	37.8	.440	.402	29.0	28.0	13.9	34.6	.437	.410	6,176	3,038
	2 a–b	10.8	31.8	.409	.389	25.0	21.0	10.5	32.4	.407	.389	6,850	2,827
	2 c–d	10.3	35.4	.414	.395	24.0	20.0	12.4	37.8	.418	.378	6,670	2,693
	5 c–d	12.0	31.5	.388	.362	16.0	20.0	12.5	32.0	.383	.368	5,170	2,747
Average		11.1	34.1	.413	.387	24.0	22.0	12.3	34.2	.411	.386	6,217	2,826

[1] Per cent moisture based on oven-dry weight.
[2] Specific gravity based on oven-dry weight and volume as tested.

Figures better suited to the comparison of runs 147 and 148 are given in Table 9. Improvement ratios derived from them are given in Table 10 and graphed in figure 10. These data differ from those of Tables 1 and 5 and figure 8 chiefly in that run 147 included no material from the central portions of the various bolts, so that in making Tables 9 and 10 and figure 10 tests on material from such central portions dried in run 148 were excluded in order to get the best possible comparison of the two runs.

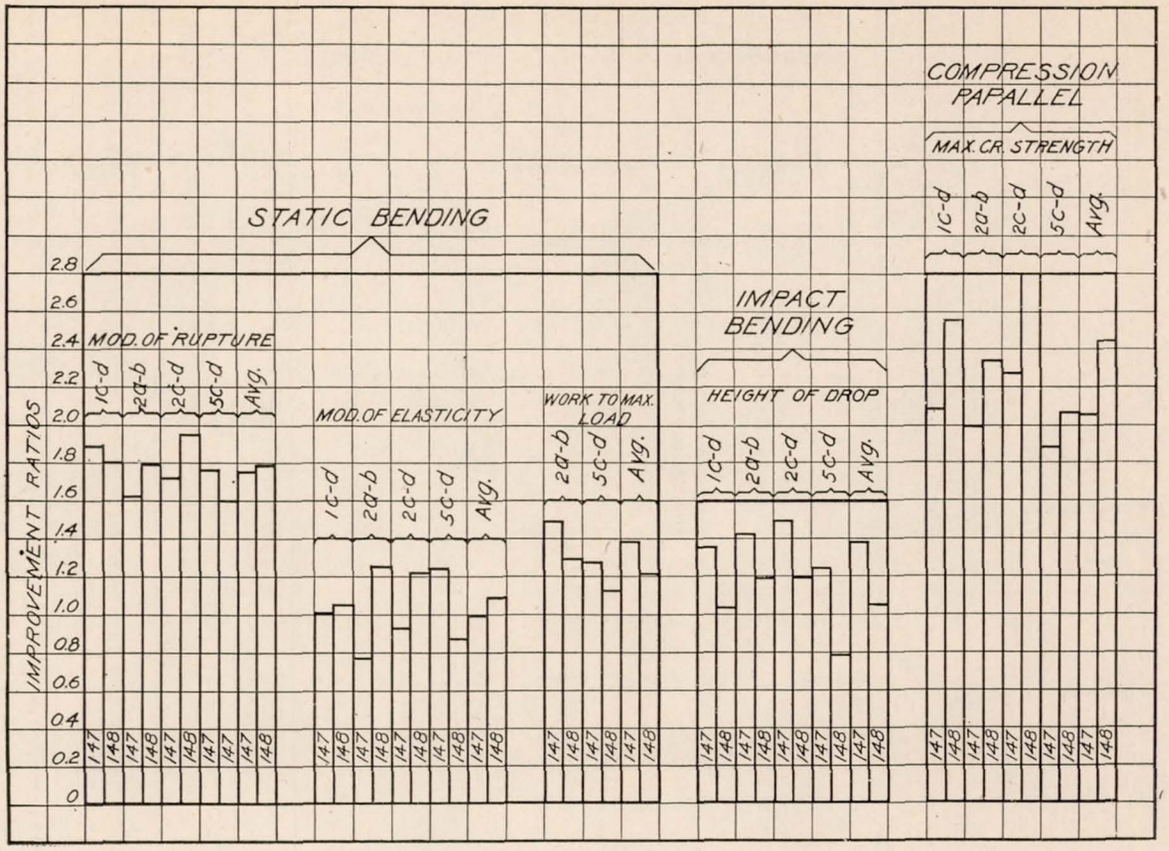


FIG. 10.—Improvement ratios for comparing kiln runs 147 and 148, Sitka spruce.

TABLE 10.—*Improvement ratios according to bolts (adjusted to 11 per cent moisture).*

[Sitka spruce: Kiln runs 147 and 148, shipment 563.]

Seasoning.	Tree and bolt.	Moisture.	Static bending.						Impact bending, 50-pound hammer.			Compression parallel to grain.		
			Modulus of rupture.		Modulus of elasticity.		Work to maximum load.		Moisture.	Height of drop.		Moisture.	Maximum crushing strength.	
			I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.
		Per ct.							*Per ct.*			*Per ct.*		
Kiln run 147 (ship. 563)	[1] 1 a–b													
	1 c–d	11.2	1.87	1.89	1.01	1.01			10.5	1.36	1.35	11.1	2.07	2.08
	2 a–b	10.5	1.65	1.62	.76	.77	1.52	1.49	10.0	1.46	1.42	10.8	2.01	1.99
	2 c–d	10.2	1.78	1.72	.93	.93			9.7	1.55	1.49	11.5	2.19	2.27
	5 c–d	9.9	1.85	1.76	1.26	1.24	1.30	1.27	10.4	1.25	1.24	10.5	1.93	1.88
Average		10.5	1.79	1.75	.99	.99	1.41	1.38	10.2	1.41	1.38	11.0	2.05	2.05
Kiln run 148[2] (ship. 563)	1 a–b													
	1 c–d	12.3	1.66	1.80	1.04	1.05	(1)	(1)	11.2	1.03	1.03	13.9	2.03	2.55
	2 a–b	9.8	1.90	1.79	1.28	1.25	1.32	1.29	10.8	1.19	1.19	10.5	2.42	2.34
	2 c–d	10.0	2.06	1.95	1.24	1.22	(1)	(1)	10.3	1.20	1.19	12.4	2.48	2.80
	5 c–d	11.5	1.57	1.60	.87	.87	1.11	1.12	12.0	.80	.78	12.4	1.88	2.06
Average		10.9	1.80	1.78	1.11	1.09	1.22	1.21	11.1	1.06	1.05	12.3	2.20	2.44

[1] Data not used since corresponding data for other kiln run are missing.
[2] Material from outer portion only—to match kiln run 147.
I. R. = Improvement ratio.

Comparisons of runs 147 and 148 (see fig. 10) in modulus of rupture, modulus of elasticity, and maximum crushing strength are erratic when individual bolts are considered, but 148 *averages* better than 147 in each of these properties. In work to maximum load and height of drop, the results are (contrary to those for small groups from the runs previously considered) consistent and quite largely in favor of run 147. This leads to the conclusion that run 148

damaged the material in work to maximum load and height of drop [1] as compared to similar material tested after drying in run 147.

That the results of run 147 are in all probability entirely satisfactory is concluded from comparison with the groups of air-dried material (fig. 8)[2].

Runs 163, 171, and 172.—Runs 171 and 172 compare very favorably with the other runs and with groups of air-dried material, except in height of drop, where they seem to be quite low.

Run 163 seems to fall below runs 171 and 172, and, in fact, below a number of the groups of material graphed in figure 8. No definite conclusions concerning these runs can be drawn until the corresponding air-dried material has been tested.

GENERAL COMPARISON OF RUNS.

Table 11 affords a means of comparing all runs. It is made up in a manner similar to Table 5, except that it gives for each run a weighted average improvement ratio instead of a weighted average "efficiency." "Efficiency" figures can not, of course, be obtained in advance of tests on corresponding air-dried material.

Table 11 indicates practically the same thing as has been brought out previously with respect to the relative merits of several of the kiln runs. It does not, however, indicate an appreciable difference between runs 147 and 148. It indicates that 163 is the poorest of all, and rather distinctly inferior to air-dried material. Very probably the apparently very poor results on run 163 are only an example of variability explainable through the fact that run 163 was on different material from the other runs. Runs 163, 171, and 172 were made on material from the same shipment, but 171 and 172 involved other trees than 163. Figures such as are given in Table 11 furnish quite accurate comparisons between two or more groups of material from the same trees. Comparisons between groups of material from different trees must, however, be modified to take into account the variations which are likely to occur.

TABLE 11.—*Sitka spruce—Average improvement ratios for all kiln runs and several groups of air-dried material.*

	Air-dry shipment 325.			Air-dry matching kiln runs 88 and 89.		Kiln run 88.		Kiln run 89.		Air-dry matching kiln runs 91, 93, and 94.		Kiln run 91.		Kiln run 93.	
	F	R	F×R	R	F×R	R	F×R	R	F×R	R	F×R	F×R	F×R	R	F×R
Modulus of rupture	2	1.81	3.62	1.80	3.60	1.88	3.76	1.78	3.56	1.90	3.80	1.88	3.76	1.85	3.70
Modulus of elasticity	4	1.30	5.20	1.18	4.72	1.29	5.16	1.21	4.84	1.36	5.44	1.28	5.12	1.39	5.56
Work to maximum load	3	1.52	4.56	1.43	4.39	1.45	4.35	1.42	4.26	1.42	4.26	1.74	5.22	1.24	3.72
Drop	3	1.18	3.54	1.08	3.24	1.12	3.36	1.05	3.15	1.03	3.09	1.21	3.63	1.11	3.33
Maximum crushing strength	2	1.97	3.94	2.37	4.74	2.22	4.44	2.24	4.48	2.37	4.74	2.25	4.50	2.61	5.22
ΣR	....	7.78	.....	7.86	.....	7.96	.....	7.70	.....	8.08	.....	8.36	.....	8.20	.....
ΣR÷5=Average R	....	1.56	.....	1.57	.....	1.59	.....	1.54	.....	1.62	.....	1.67	.....	1.64	.....
Σ(F×R)	....	.....	20.86	.....	20.59	.....	21.07	.....	20.29	.....	21.13	.....	22.23	.....	21.53
Σ (F × R) ÷ Σ F = Weighted average R	....		1.49	.....	1.47	.....	1.51	.....	1.45	.....	1.52	.....	1.59	.....	1.54
Ave. R (kiln dry)	....	.....	.....	.....	.....	.....	1.02	.....	.986	.....	.....	.....	1.046	.....	1.013
Ave. R (air dry)															

	Kiln run 94.			Kiln run 147.		Kiln run 148.		Kiln run 163		Kiln run 171.		Kiln run 172.	
	F	R	F×R	R	F×R	R	F×R	R	F×R	R	F×R	R	F×R
Modulus of rupture	2	1.94	3.88	1.78	3.56	1.78	3.56	1.82	3.64	1.93	3.86	2.01	4.02
Modulus of elasticity	4	1.36	5.44	1.07	4.28	1.14	4.56	1.16	4.64	1.30	5.20	1.31	5.24
Work to maximum load	3	1.35	4.05	1.53	4.59	1.45	4.35	1.29	3.87	1.49	4.47	1.41	4.23
Drop	3	1.27	3.81	1.36	4.08	1.03	3.09	.97	2.91	.93	2.79	.90	2.70
Maximum crushing strength	2	2.38	4.76	2.10	4.20	2.42	4.84	1.89	3.78	2.27	4.54	2.47	4.82
ΣR	....	8.30	.....	7.84	.....	7.82	.....	7.13	.....	8.02	.....	8.10	.....
ΣR÷5=Average R	....	1.66	.....	1.57	.....	1.56	.....	1.43	.....	1.60	.....	1.62	.....
Σ(F×R)	....	.....	21.94	.....	20.71	.....	20.40	.....	18.84	.....	20.86	.....	21.01
Σ(F×R)÷ΣF= Weighted average R	....	.....	1.57	.....	1.48	.....	1.46	.....	1.35	.....	1.49	.....	1.50
Ave. R (kiln dry)	....	.....	1.035	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Ave. R (air dry)													

R=Improvement ratio adjusted to 11 per cent moisture.
F=Weighting factor.

[1] This falling down in these properties, while excellent results were secured in modulus of rupture and maximum crushing strength, is in accordance with results previously obtained from tests on the effect of other treatments and of incipient decay. It has been found in such tests that quite severe damage to shock resisting ability (as indicated by work and drop values) may occur without any detectable effect on static strength as indicated by modulus of rupture and maximum crushing strength.

[2] It is notable that run 148 might be looked upon as fairly satisfactory were it compared to the data of figure 8, exclusive of run 147.

PHOTOGRAPHS OF FAILURES.

Plates I to IX, inclusive, show failures of impact-bending sticks from various kiln runs and from some air-dried material. Plates I, II, and III, pertaining to run 148, are of particular interest. The possible value and interest of such photographs was not suggested until the time of the testing of these sticks. It is unfortunate that similar photographs from earlier runs, particularly 147, are not available.

Of the failures shown in Plate I more than one-third would be judged to be of the highest type and in no way indicative of the brashness shown by the data of Tables 9 and 10 and figure 10. In Plate II but one or two of the failures are at all indicative of brashness, and it is difficult to believe that this material has been injured. That such is the case, however, seems to be very definitely shown by the test results. All but one, or possibly two, of the failures shown in Plate III are indicative of very poor material.

Plates IV to VII show failures of sticks from runs 171 and 172, and of corresponding green sticks. Failures of air-dried sticks corresponding to kiln runs 88 and 89 are shown in Plate VIII, and to runs 91, 93, and 94 in Plate IX. Comparison of these various photographs fails to indicate any difference between the air-dried and kiln-dried material with respect to types of failure.

Plates I, II, and III as brought out by the comment on them and comparison with the strength data show that reliable conclusions as to the effect of kiln drying can not be attained by inspection of failures.

RÉSUMÉ FOR SITKA SPRUCE.

Because of the importance of Sitka spruce as an airplane material, and in order to set forth the methods of analysis used and to illustrate the difficulties met and the caution necessary in making such an analysis, the data on Sitka spruce have been discussed in greater detail than is considered necessary for the other species.

Data concerning 10 kiln runs are presented. These 10 runs include 5 runs, material from which is compared to matched material tested after air drying, and 5 for which data on matched air-dried material are not available.

It is shown conclusively that Sitka spruce can be kiln dried without loss of strength as compared to air drying.

In connection with this and other conclusions stated in this report it is desired to call attention to the fact that the material which was kiln dried is compared to material air dried under conditions probably much more favorable to good results than is ordinarily the case. This material was also air dried in small sticks ($2\frac{1}{2}$ by $2\frac{1}{2}$ inches in cross-section). This procedure is undoubtedly more favorable to the retention of maximum strength than is air drying in wider planks, as is ordinarily done. In fact, casehardening of sticks of this size was purposely attempted in one kiln run (not discussed herein) but without success.

Data on the first five runs fail to disclose any consistent relation between the temperatures used in drying and the strength of the resulting material, and taken by themselves would lead to the conclusion that temperatures up to 130° F. can be safely used. There is, however, quite conclusive evidence of damage to material dried in one of the other runs made with temperatures between 160° and 180° F. Taken as a whole, therefore, the data presented do not justify the use of temperatures as high as 160° F. Definite evidence as to what is the critical temperature which should never be exceeded is not afforded.

It is believed, however, that the data presented justify the conclusion that the temperatures of specification 20500–A (120° F. initial to 145° F. final) are entirely safe.

There is no evidence of the extreme brashness which has been claimed to result from kiln drying.

RECOMMENDATIONS.

Because of the possibility of damage from higher temperature and the fact that as the scheduled temperature is increased the danger of damage through accidental departure from schedule increases, it is recommended that the temperatures of Table 1 of Specification 20500–A (see Appendix A of Report No. 65, "Kiln Drying of Wood for Airplanes") be not exceeded in the drying of Sitka spruce for airplane stock.

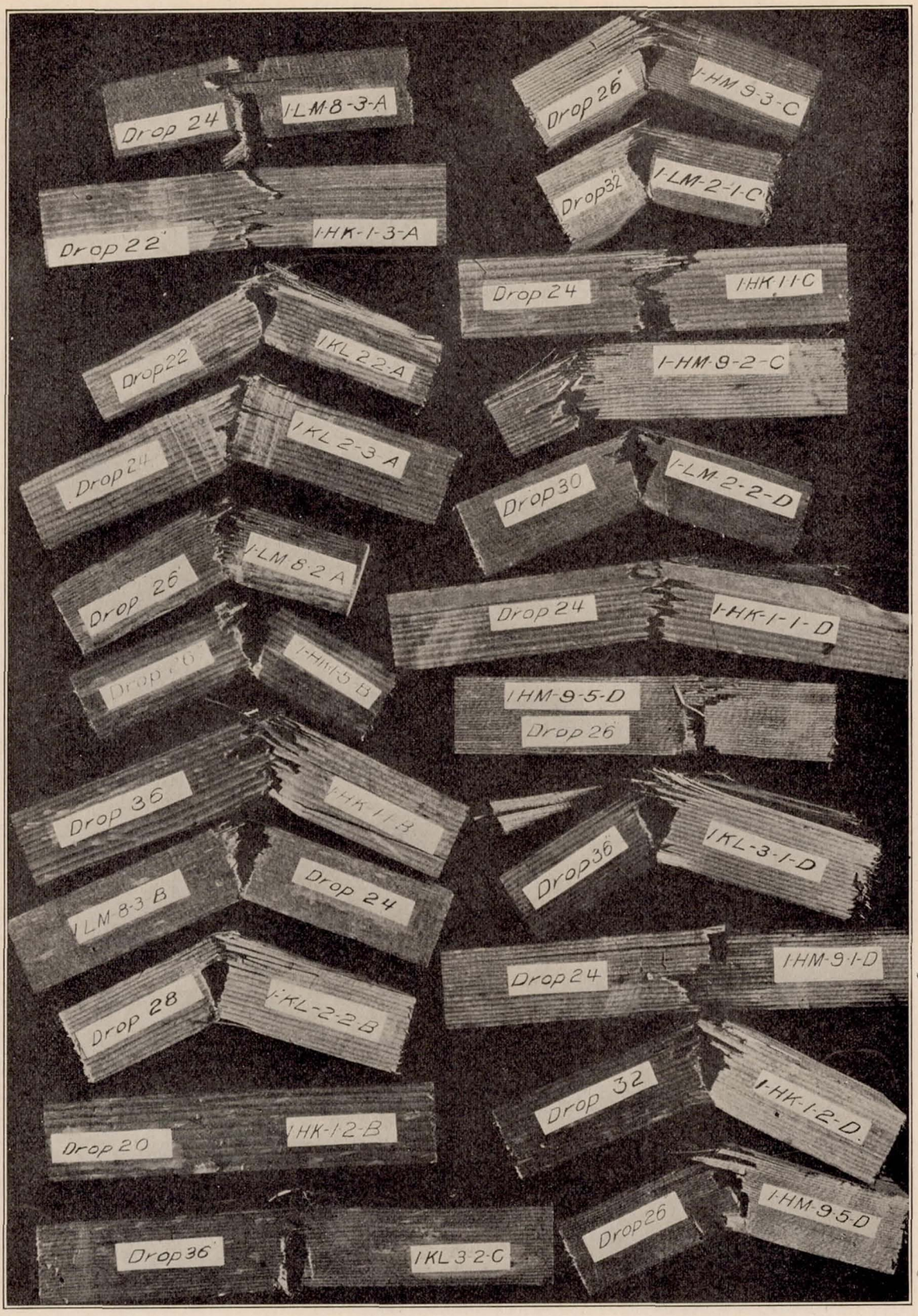


PLATE I.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, KILN RUN 148.

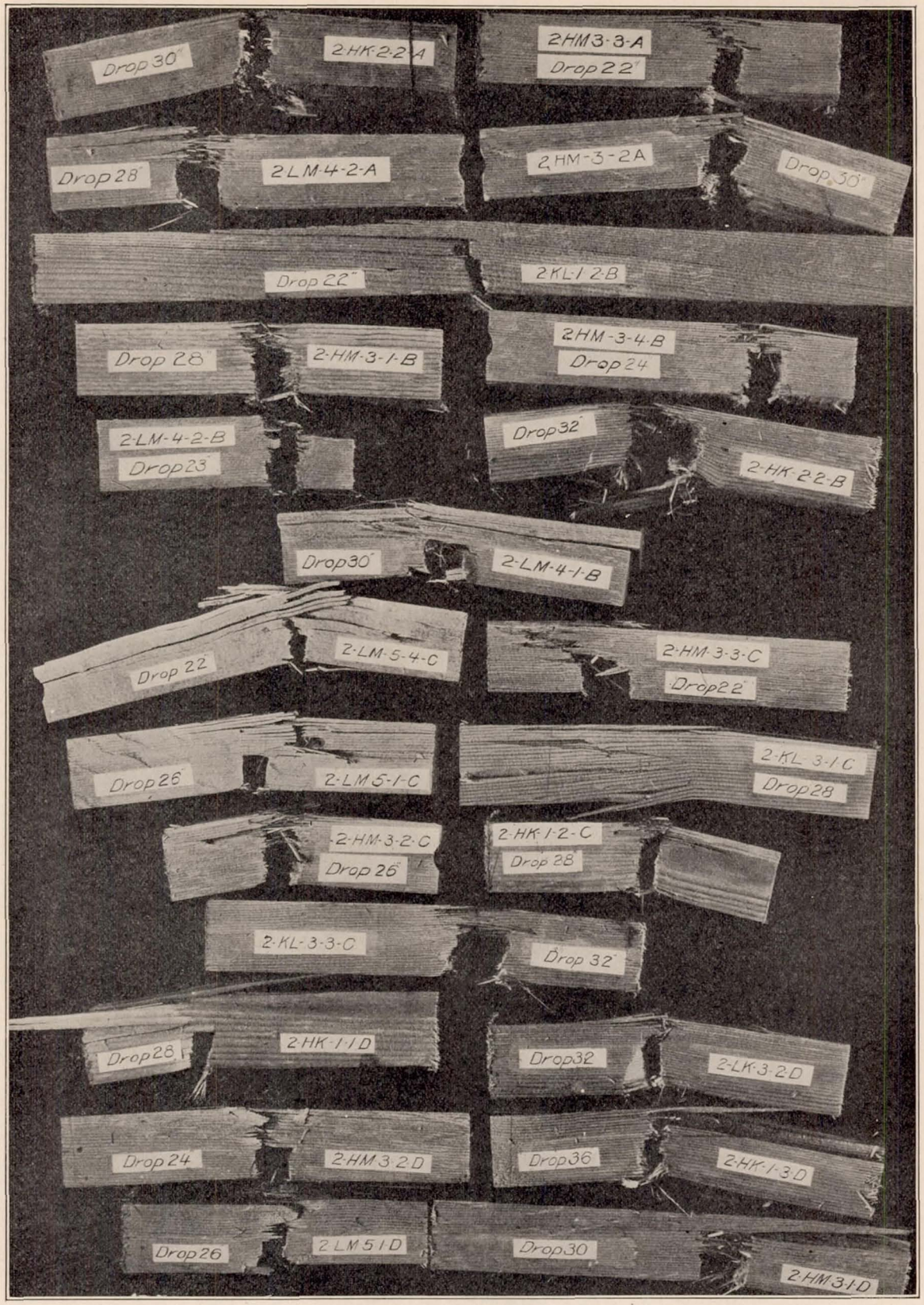


PLATE II.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, KILN RUN 148.

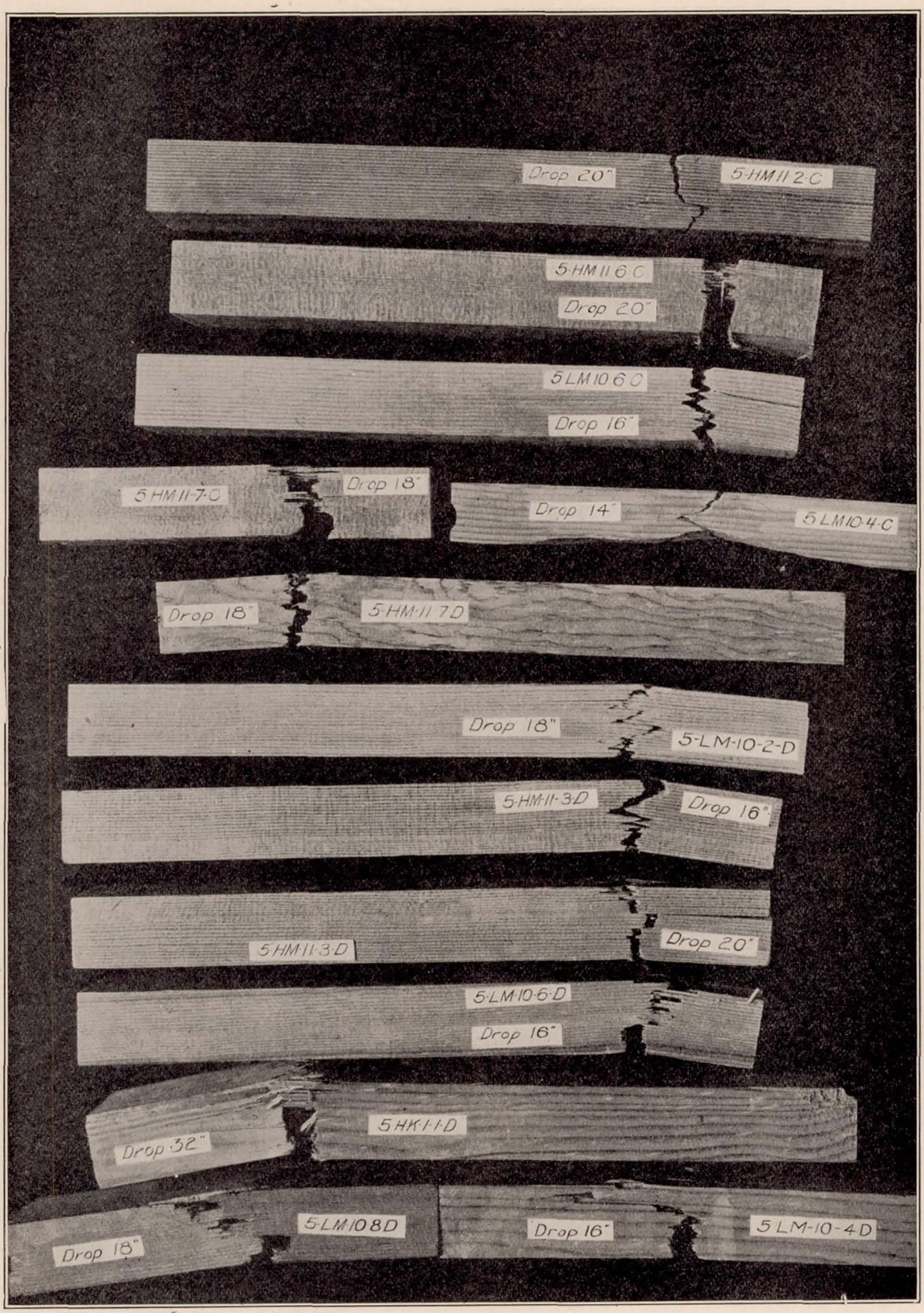


PLATE III.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, KILN RUN 148.

506–3

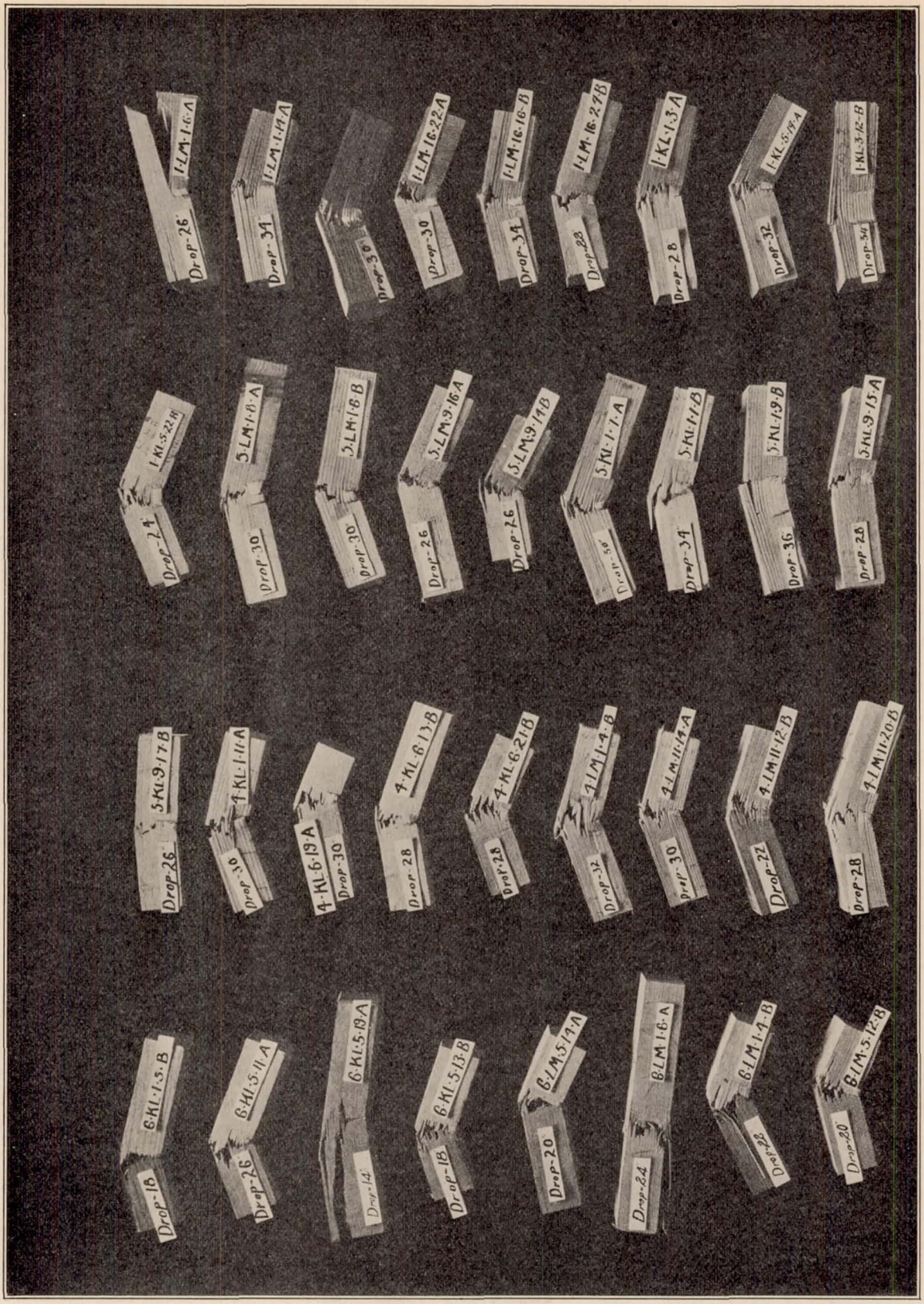


PLATE IV.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, GREEN, MATCHING KILN RUN 171.
506–4

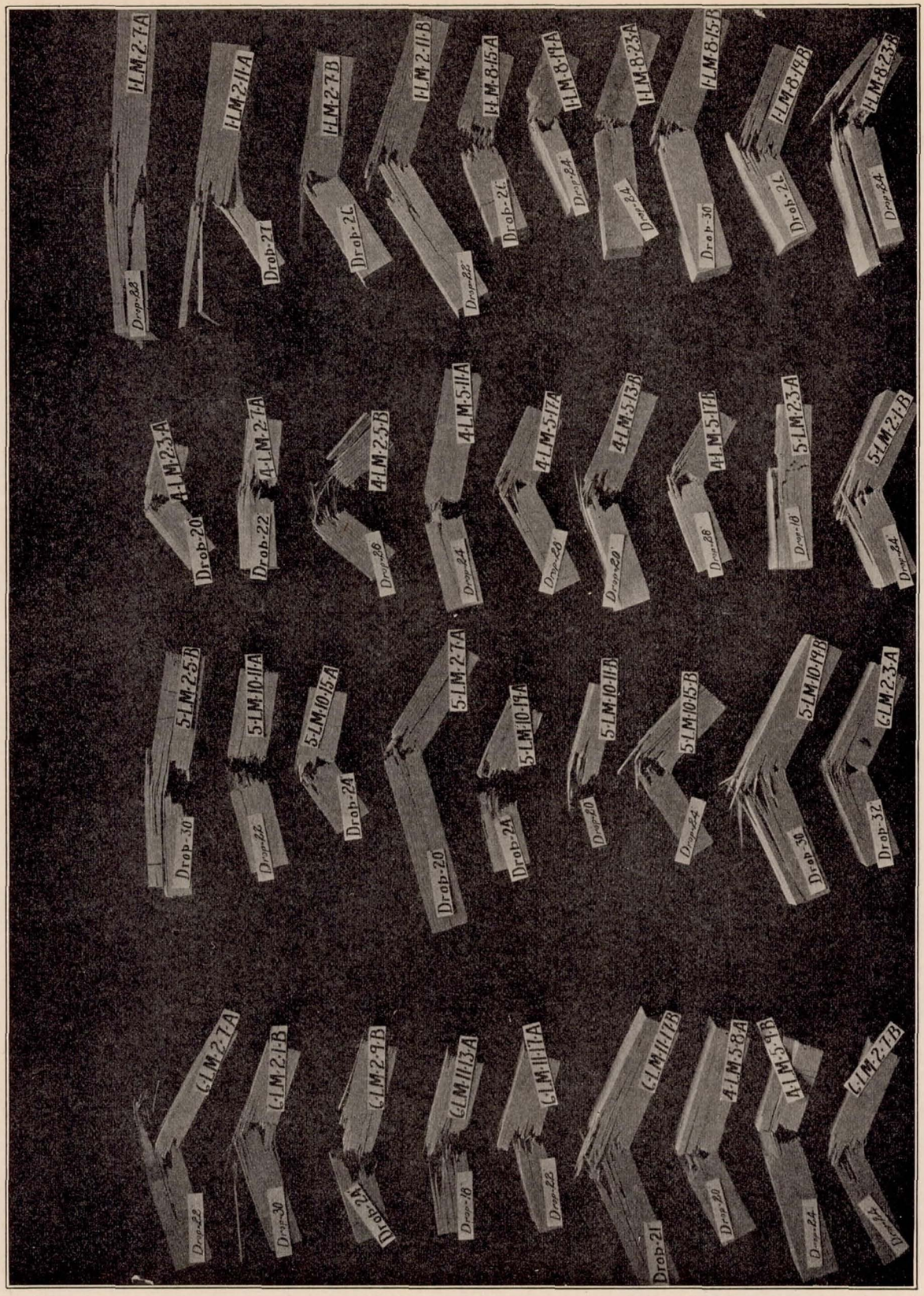


PLATE V.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, KILN RUN 171.

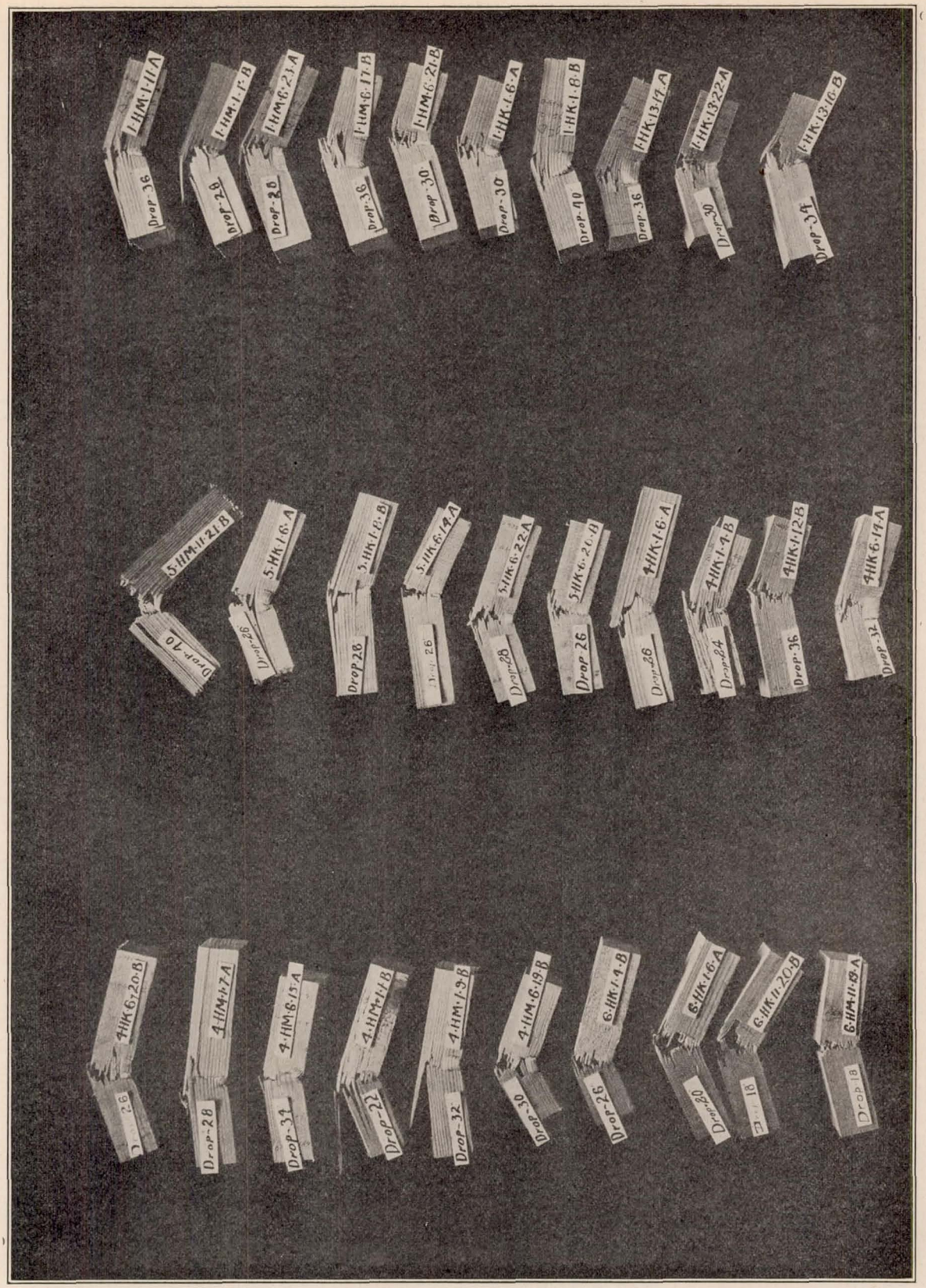


PLATE VI.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, GREEN, MATCHING KILN RUN 172.
506-6

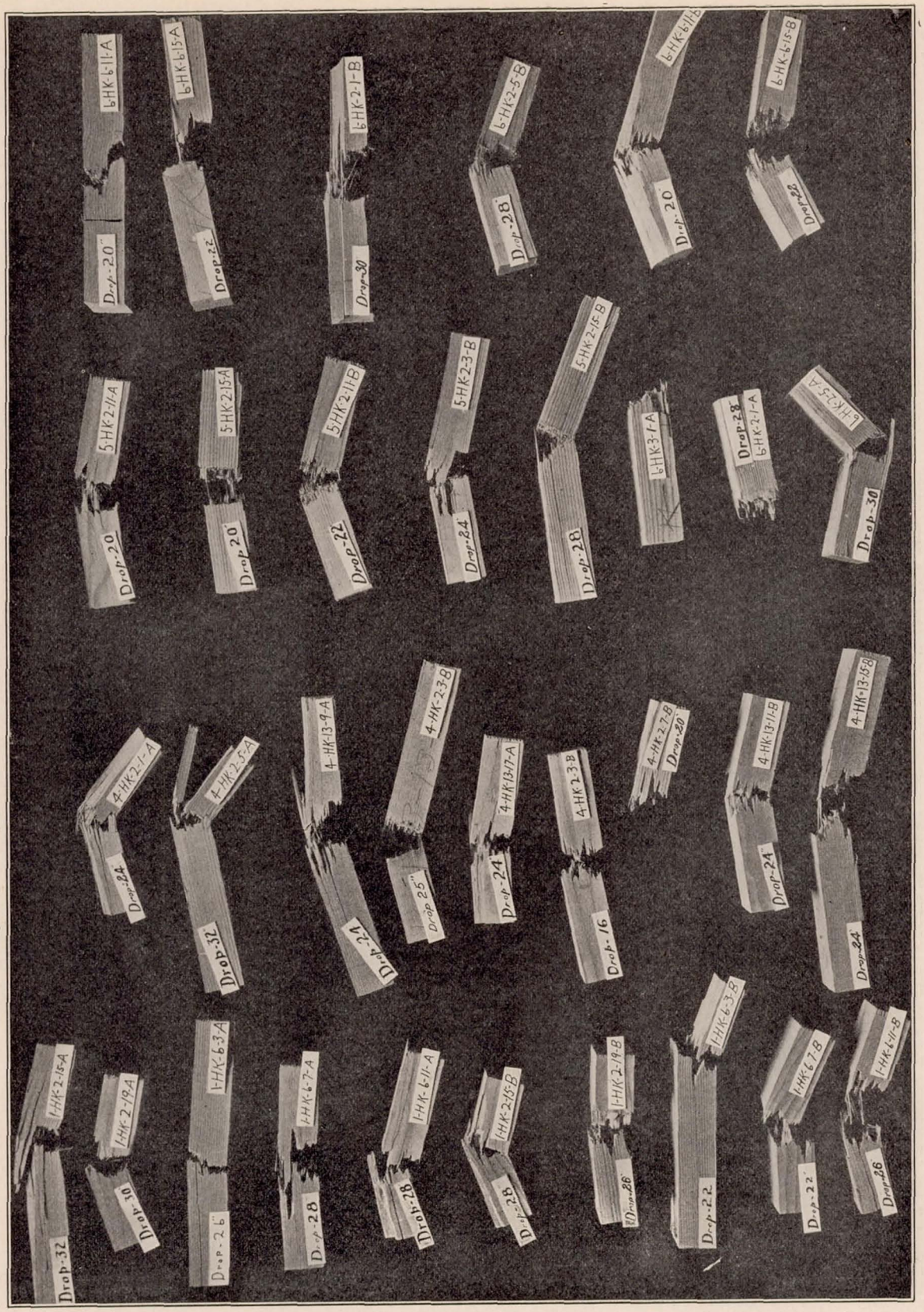


PLATE VII.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, KILN RUN 172.

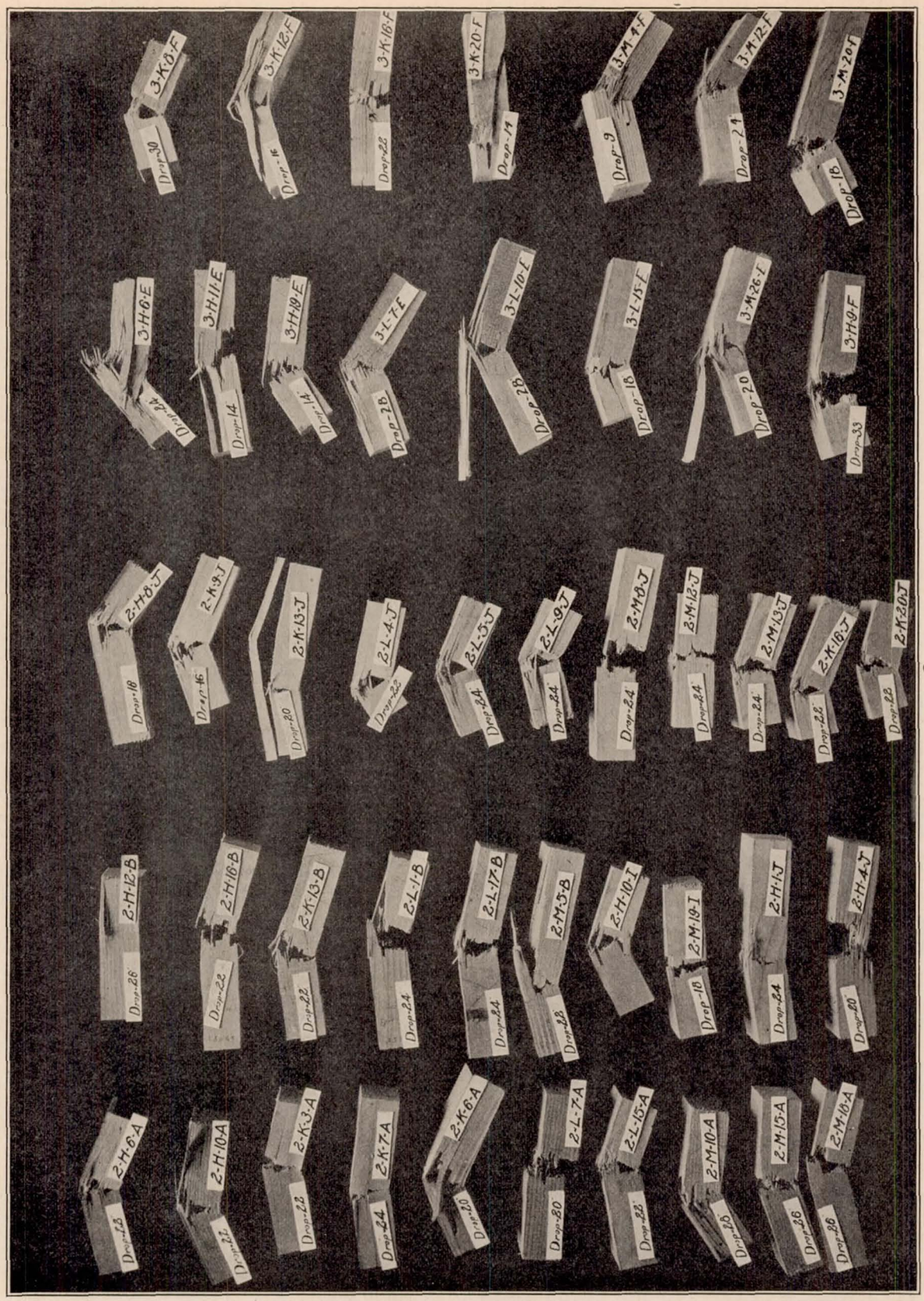


PLATE VIII.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, AIR-DRIED, MATCHING KILN RUNS 88 AND 89.

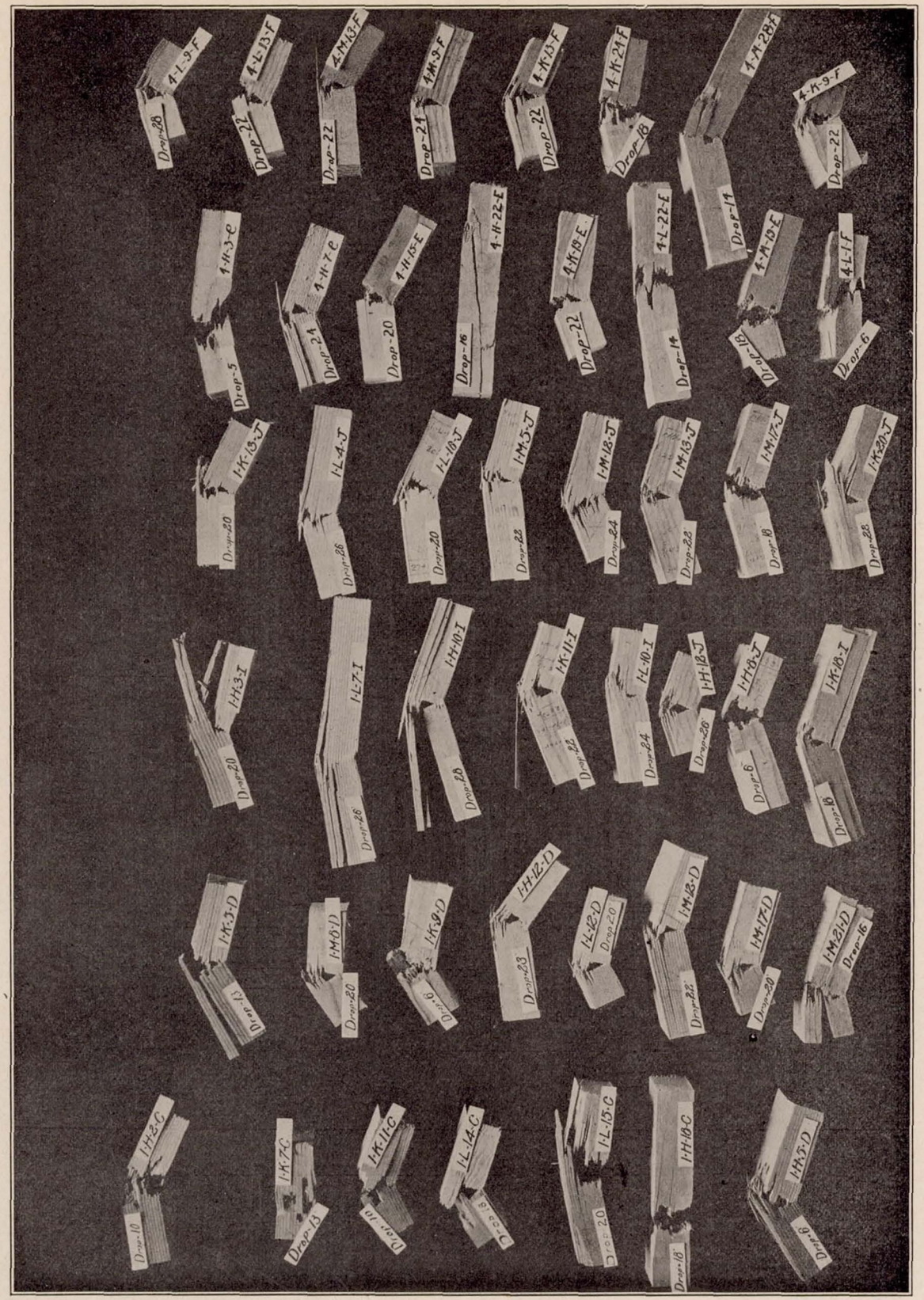


PLATE IX.—FAILURES OF IMPACT-BENDING SPECIMENS, SITKA SPRUCE, AIR-DRIED, MATCHING KILN RUNS 91, 93, AND 94.

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DOUGLAS FIR.

SOURCE OF MATERIAL.

The material for the four experimental runs on Douglas fir was derived from 10 trees which were grown along the lower Columbia River, in Clatsop County, Oregon, at an elevation of about 1,500 feet. Each tree was represented by two 8-foot logs, an upper bolt (*h-i*, *i-j*, or *m-n*) and a lower bolt (*a-b*), making in all twenty 8-foot bolts. The logs varied in size from 31 inches to 39 inches in diameter and were from 300 to 350 years old. This material constituted shipment 523.

The logs were sawed into 2-inch and 3-inch planks of various widths. Specimens for test in the green and air-dried conditions were obtained from two flitches extending from side to side and nearly through the center of each 8-foot log. (See fig. 1 (B).) The sticks from each 8-foot bolt were grouped as outlined on page 15.

The remaining material was divided among the four kiln runs. Figure 1 (B) is an example showing how planks for test after kiln drying were selected. Figure 1 (D) shows how these planks were divided into test specimens and how the latter were marked. Table 12 is a schedule showing the distribution of material from these 10 trees among the four kiln runs. Previously tested green and air-dried material, with which comparisons are made, was secured from two trees from shipment 315, two from shipment 318, and one from shipment 354. These shipments were from Lewis County, Wash., Lane County., Oreg., and Humboldt County, Calif., respectively.

TABLE 12.—*Douglas fir. Shipment 523. List of trees and bolts to show which bolts were represented in the various kiln runs.*

Tree and bolt.	Kiln run 99.	Kiln run 101.	Kiln run 102.	Kiln run 103.
1 a–b	*	*		
1 i–j	*	*		
2 a–b	*	*		
2 k–l			*	*
3 a–b			*	*
3 m–n	*	*		
4 a–b	*	*		
4 h–i			*	*
5 a–b			*	*
5 h–i	*	*		
6 a–b	*	*		
6 i–j			*	*
7 a–b			*	*
7 i–j	*	*		
8 a–b	*	*		
8 h–i			*	*
9 a–b			*	*
9 k–l	*	*		
10 a–b			*	*
10 h–i			*	*

* Indicates that material from the bolt listed at the left was included in the kiln run whose number appears at the top of the column.

DESCRIPTION OF KILN-DRYING CONDITIONS.

Figure 11 is a graphical representation of the kiln conditions and of the moisture contents of samples of the stock for the four runs 99, 101, 102, and 103.

In every case material went into the kiln soon after cutting from the log and before any appreciable drying had occurred.

Kiln run 99.—The charge for run 99 consisted of two hundred twenty-nine 2 by 3 inch, 4 by 5 inch, and 3 by 4 inch pieces. Arrangement of the kiln was practically the same as shown in figure 7 (kiln run 147), except that the stock was flat-piled with 2 to 3 inches between the pieces in each layer. Two-inch stickers were used.

After a preliminary steaming at 130° F. for four hours, drying was started at 120° F. and about 90 per cent relative humidity. Temperature and humidity were gradually changed, as shown by the curves, to about 125° F. and 55 per cent humidity at the end of the run.

Casehardening, though not apparent at the close of the run, was discovered after removal of the material from the kiln. It was accordingly reloaded, steamed for two and one-half hours at 150° F. for the removal of casehardening, and then redried.

Inspection showed that less than 1 per cent degrade occurred in this run.

Kiln run 101.—Run 101 was made in a curtain kiln the arrangement of which is shown in figure 12.

The charge consisted of 2-inch and 3-inch material of various widths and derived from the same bolts as that for run 99.

After a preliminary steaming at 120° F. drying was begun at 105° F. and 80 per cent relative humidity. These conditions were gradually changed, as shown by figure 20, to 120°

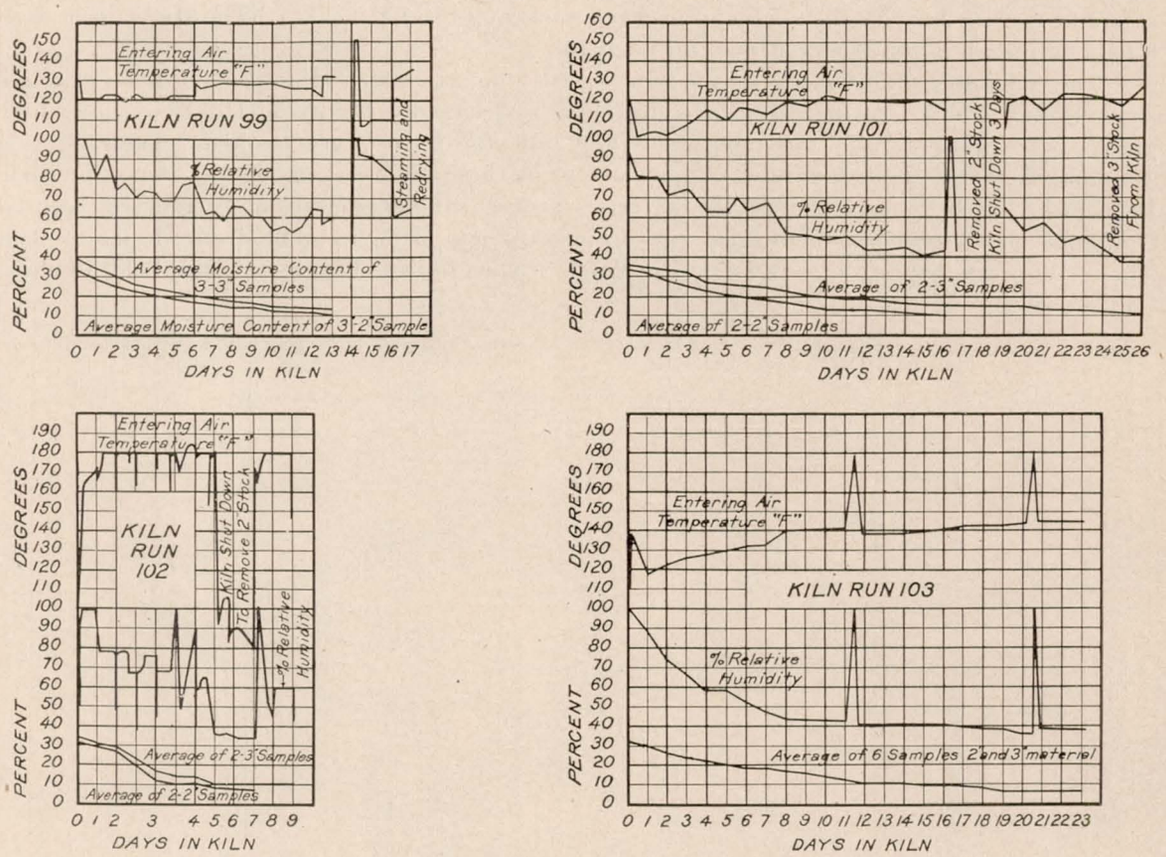


FIG. 11.—Kiln conditions for Douglas fir, kiln runs 99, 101, 102, and 103 (shipment 523).

F. and 40 per cent relative humidity at the end of the run. Steaming at 133° F. was used on the sixteenth day to remove casehardening.

Less than 1 per cent degrade occurred, as shown by inspection before and after kiln drying.

Kiln run 102.—The arrangement of the kiln for run 102 was practically as shown in figure 5 (run 89). The stock consisted of 2-inch and 3-inch planks of various widths. After preliminary steaming at about 165° F. the temperature was raised to about 180° F., where it was kept for the remainder of the run. The initial humidity (after steaming) was 80 per cent. Steaming at 180° F. was used once to remove casehardening.

Kiln run 103.—Figure 13 shows the kiln arrangement for run 103. The stock was 2-inch and 3-inch planks of various widths. After preliminary steaming at 138° F. drying was begun with a temperature of 117° F. and relative humidity of 85 per cent. These conditions were gradually changed to 142° F. and about 37 per cent relative humidity at the close of the run.

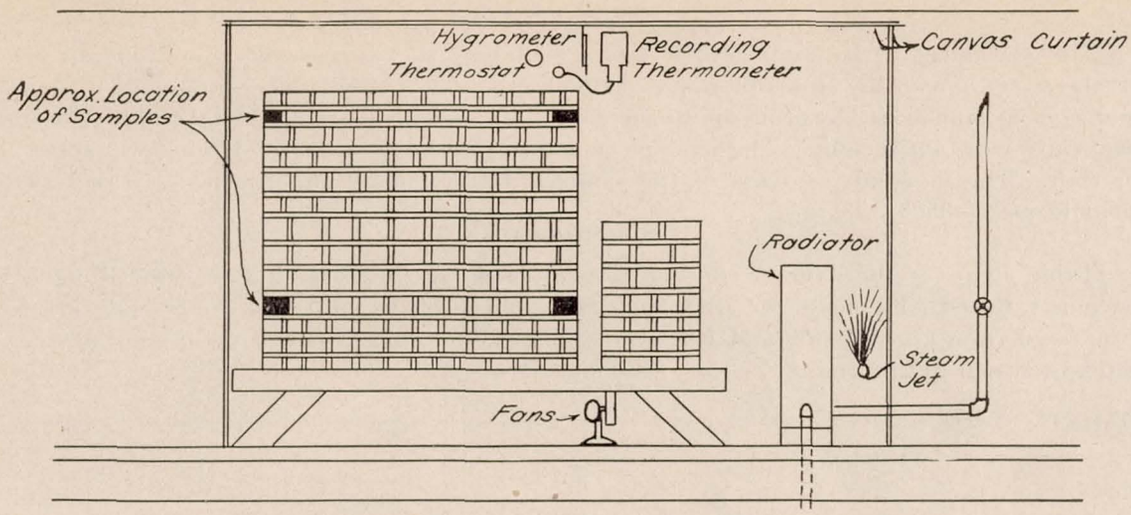


FIG. 12.—Cross section of kiln and piling diagram, Douglas fir kiln run 101.

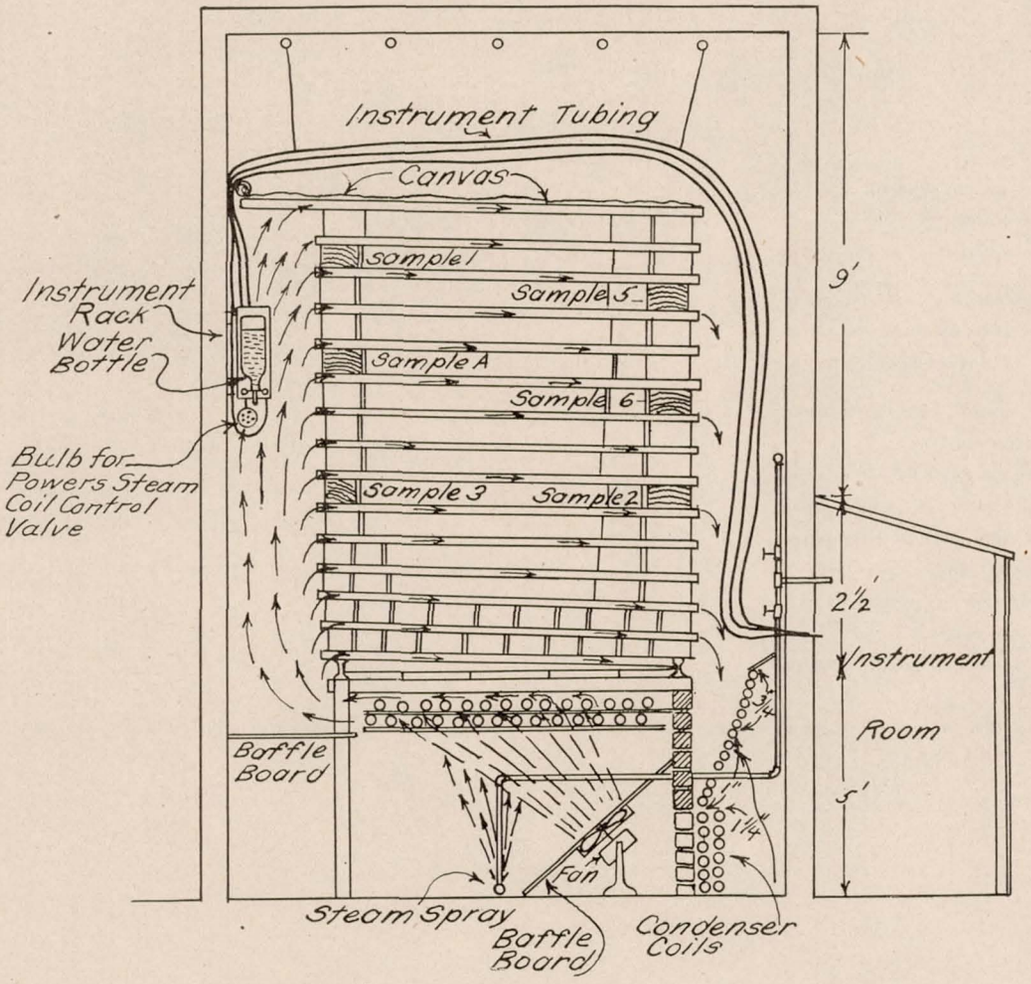


FIG. 13.—Cross section kiln and piling diagram, Douglas fir kiln run 103.

THE AIR DRYING.

Test specimens 2½ by 2½ inches by 4 feet, matching the various kiln runs, were air dried for about eight months, from February, 1918, to October, 1918, under practically the same conditions as similar Sitka spruce specimens (see p. 25), when they were found to have reached practically constant weight. The average moisture content at time of storing was about 31 per cent. The moisture contents of the samples at the end of the air-drying periods were about 12 per cent.

STRENGTH DATA.

Table 13 gives the average mechanical properties of the green and air-dried Douglas fir previously tested (shipments 315, 318, and 354); and also—by butt and upper bolt classes—of material from kiln runs 99 and 101, and from runs 102 and 103, with green and air-dry to match each pair of kiln runs.

TABLE 13.—*Average mechanical properties of Douglas fir.* (*Tabulations of test results without moisture adjustment.*)

Property.	Various shipments.		Shipment 523.							
			Lower bolts.							
	Ship. 315 315 318 318 354	Tree. 1 6 6 8 3	Green, to match kiln runs 99 and 101.	Air dry, to match kiln runs 99 and 101.	Kiln run 99.	Kiln run 101.	Green, to match kiln runs 102 and 103.	Air dry, to match kiln runs 102 and 103.	Kiln run 102.	Kiln run 103.
	Green.	Air dry.								
STATIC BENDING.										
Moisture (per cent)[1]	39.8	6.4	36.9	12.0	11.0	11.5	33.7	12.2	13.3	9.1
Specific gravity[2]	.467	.526	.465	.494	.500	.518	.453	.484	.501	.487
Fiber stress at elastic limit (lbs. per sq. in.)	7,825	11,437	4,810	8,540	9,720	9,491	4,910	8,280	8,072	10,450
Modulus of rupture (lbs. per sq. in.)	5,100	15,242	7,860	12,510	13,360	3,6091	7,980	12,270	11,105	13,550
Modulus of elasticity (1,000 lbs. per sq. in.)	1,684	2,184	1,550	1,859	1,922	2,039	1,535	1,791	1,842	1,704
Work to elastic limit (inch-lbs. per cu. in.)			.87	2.21	2.73	2.53	.91	2.16	2.0	3.79
Work to maximum load (inch-lbs. per cu. in.)	6.6	9.1	8.2	9.5	10.4	9.9	8.2	9.1	7.7	9.0
IMPACT BENDING: 50-POUND HAMMER.										
Moisture (per cent)[1]	41.4	6.4	33.5	12.1	10.8	11.5	33.1	12.2	12.3	9.6
Specific gravity[2]	.463	.528	.490	.499	.498	.517	.455	.480	.499	.489
Fiber stress at elastic limit (lbs. per sq. in.)	10,103	15,605	10,140	13,730	12,387	13,930	9,120	13,350	13,122	13,050
Modulus of elasticity (1,000 lbs. per sq. in.)	1,817	2,371	1,788	2,106	2,158	2,503	1,547	1,987	2,327	2,250
Work to elastic limit (inch-lbs. per cu. in.)	3.2	6.1	3.2	5.0	3.9	4.4	13.0	5.0	4.2	4.1
Drop causing complete failure (inches)	23.9	34.9	24	28.2	27.4	29.0	22.0	28.1	25.0	30.4
COMPRESSION PARALLEL TO GRAIN.										
Moisture (per cent)[1]	37.9	6.4	33.5	12.3	10.9	11.7	32.5	11.9	10.9	8.8
Specific gravity[2]	.459	.504	455	.491	.497	.514	.451	.482	.498	.483
Maximum crushing strength (lbs. per sq. in.)	4,060	11,233	3,850	7,540	7,921	8,250	3,850	7,320	7,220	8,640

[1] Per cent moisture based on oven-dry weight.

[2] Specific gravity based on oven-dry weight and volume as tested.

TABLE 13.—*Average mechanical properties of Douglas fir*—Continued.

Property.	Shipment 523. Upper bolts. Green, to match kiln runs 99 and 101.	Air dry, to match kiln runs 99 and 101.	Kiln run 99.	Kiln run 101.	Green, to match kiln runs 102 and 103.	Air dry, to match kiln runs 102 and 103.	Kiln run 102.	Kiln run 103.
STATIC BENDING.								
Moisture (per cent) [1]	30.3	12.3	10.4	10.9	29.4	11.7	12.4	9.3
Specific gravity [2]	.411	.452	.433	.436	.435	.474	.476	.480
Fiber stress at elastic limit (lbs. per sq. in.)	4,320	7,590	8,811	8,917	4,880	7,930	7,544	9,540
Modulus of rupture (lbs. per sq. in.)	7,070	11,380	11,563	11,860	7,560	11,820	10,520	12,562
Modulus of elasticity (1,000 lbs. per sq. in.)	1,421	1,738	1,697	1,768	1,522	1,761	1,765	1,631
Work to elastic limit (inch-lbs. per cu. in.)	.76	1.87	2.59	2.55	.91	2.03	1.84	3.27
Work to maximum load (inch-lbs. per cu. in.)	6.6	8.6	8.6	8.2	6.8	8.6	7.5	7.9
IMPACT BENDING: 50-POUND HAMMER.								
Moisture (per cent) [1]	31.1	12.0	10.4	10.5	30.1	11.9	11.2	9.1
Specific gravity [2]	.407	.435	.429	.435	.432	.481	.479	.483
Fiber stress at elastic limit (lbs. per sq. in.)	9,560	11,880	11,814	12,520	8,850	13,260	12,970	12,730
Modulus of elasticity (1,000 lbs. per sq. in.)	1,713	1,796	2,012	2,135	1,509	1,986	2,243	2,282
Work to elastic limit (inch-lbs. per cu. in.)	3.0	4.4	3.9	4.2	2.9	5.0	4.2	4.0
Drop causing complete failure (inches)	20.0	22.7	23.9	24.0	19.0	26.2	23.0	28.1
COMPRESSION PARALLEL TO GRAIN.								
Moisture (per cent) [1]	29.9	12.1	9.8	11.0	30.9	11.9	9.9	8.8
Specific gravity [2]	.409	.440	.432	.432	.432	.475	.472	.481
Maximum crushing strength (lbs. per sq. in.)	3,630	6,810	7,358	7,496	3,900	7,230	7,440	8,740

[1] Per cent moisture based on oven-dry weight. [2] Specific gravity based on oven-dry weight and volume as tested.

Table 14 presents the average improvement ratios for the more important properties of the various groups of air-dried and kiln-dried material. These ratios are derived from Table 13 and are given both with and without adjustment to a uniform moisture content (11 per cent).

TABLE 14.—*Average improvement ratios of Douglas fir (with and without adjustment to 11 per cent moisture).*

[Shipment 523.]

Seasoning.	Bolt.	Static bending. Moisture.	Modulus of rupture. I. R. as tested.	Modulus of rupture. I. R. adjusted.	Modulus of elasticity. I. R. as tested.	Modulus of elasticity. I. R. adjusted.	Work to maximum load. I. R. as tested.	Work to maximum load. I. R. adjusted.	Impact bending. Moisture.	Height of maximum drop. I. R. as tested.	Height of maximum drop. I. R. adjusted.	Compression parallel to grain. Moisture.	Maximum crushing strength. I. R. as tested.	Maximum crushing strength. I. R. adjusted.
Air dry to match kiln runs		*P. ct.*							*P. ct.*			*P. ct.*		
99 and 101	a–b	12.0	1.59	1.66	1.20	1.22	1.16	1.17	12.1	1.18	1.20	12.3	1.96	2.13
Kiln run 99	a–b	11.0	1.70	1.70	1.24	1.24	1.27	1.27	10.8	1.14	1.14	10.9	2.06	2.05
Kiln run 101	a–b	11.5	1.74	1.79	1.32	1.33	1.21	1.22	11.5	1.21	1.22	11.7	2.14	2.25
Air dry to match kiln runs														
102 and 103	a–b	12.2	1.54	1.61	1.17	1.19	1.11	1.12	12.2	1.28	1.31	11.9	1.90	2.00
Kiln run 102	a–b	13.3	1.39	1.51	1.20	1.25	.94	.93	12.3	1.14	1.15	10.9	1.88	1.87
Kiln run 103	a–b	9.1	1.70	1.58	1.11	1.09	1.10	1.09	9.6	1.38	1.34	8.8	2.24	1.98
Air dry [1]	Upper.	6.4	1.95	1.62	1.30	1.21	1.38	1.26	6.4	1.46	1.32	6.4	2.77	2.08
Air dry to match kiln runs														
99 and 101	...do...	12.3	1.61	1.71	1.22	1.25	1.30	1.35	12.0	1.14	1.15	12.1	1.88	2.00
Kiln run 99	...do...	10.4	1.64	1.60	1.19	1.18	1.30	1.29	10.4	1.20	1.19	9.8	2.03	1.90
Kiln run 101	...do...	10.9	1.68	1.67	1.25	1.24	1.24	1.24	10.5	1.20	1.19	11.0	2.06	2.06
Air dry to match kiln runs														
101 and 102	...do...	11.7	1.56	1.61	1.16	1.17	1.27	1.28	11.9	1.38	1.42	11.9	1.85	1.95
Kiln run 102	...do...	12.4	1.39	1.45	1.16	1.18	1.10	1.12	11.2	1.21	1.21	9.9	1.91	1.81
Kiln run 103	...do...	9.3	1.66	1.56	1.07	1.06	1.16	1.14	9.1	1.48	1.40	8.8	2.24	1.98

[1] Average of 5 trees of previously tested air-dried material, contained in the (c–d), (d–e), and (e–f) bolts, shipments 315, 318, and 354.
I. R.=Improvement ratio.

The improvement ratios from Table 13 are graphed in figure 14.

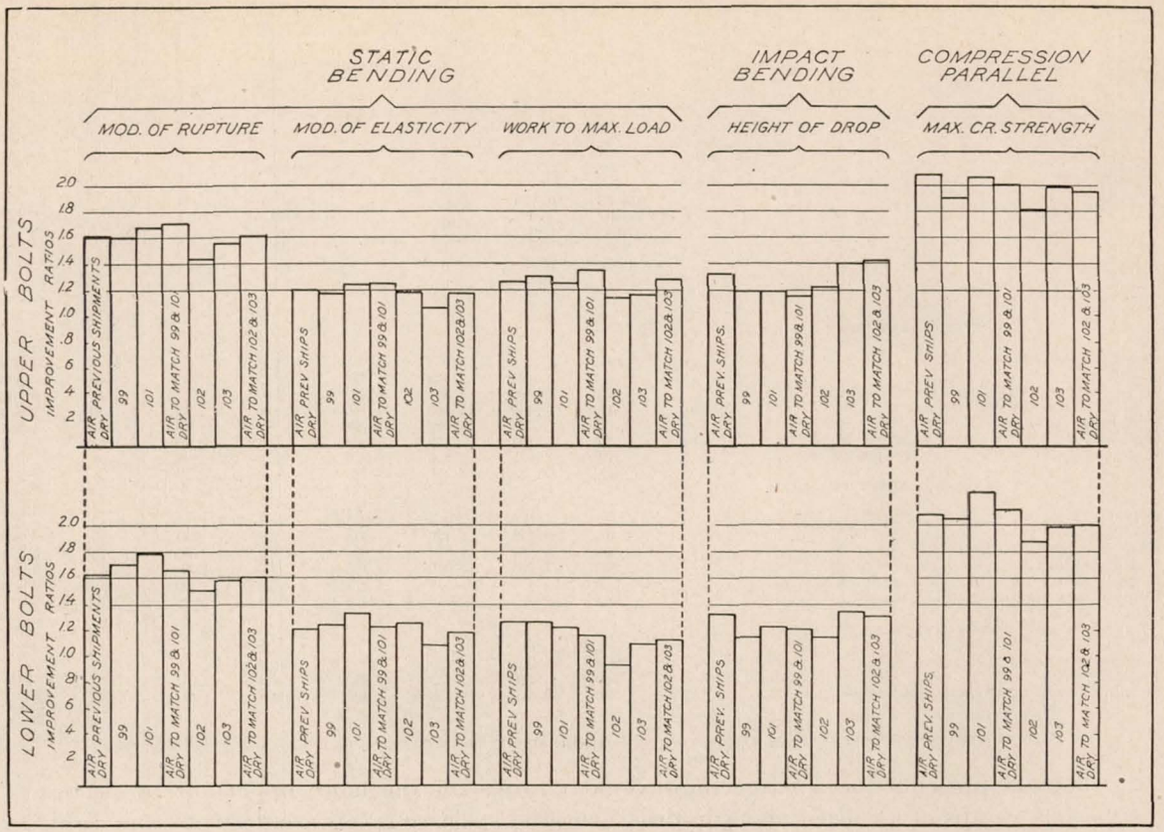


FIG. 14.—Improvement ratios for comparison of kiln-dried and air-dried stock, Douglas fir.

Table 15, similar to Tables 6, 7, and 8 for Sitka spruce, give efficiencies for upper and lower bolts, respectively.

TABLE 15.—*Efficiencies for kiln runs on Douglas fir.*

(A)—UPPER BOLTS.

Property.	F.	Kiln run 99.		Kiln run 101.		Kiln run 102.		Kiln run 103.	
		E.	E×F.	E.	E×F.	E.	E×F.	E.	E×F.
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	93.6	187.2	97.4	194.8	89.4	178.8	97.0	194.0
Modulus of elasticity	4	93.6	374.4	99.2	396.8	100.9	403.6	90.6	362.4
Work to maximum load	3	88.9	266.7	91.8	275.4	89.0	267.0	90.6	271.8
Drop	3	103.6	310.8	103.6	310.8	86.6	259.8	98.5	295.5
Compression	2	95.0	190.0	103.0	206.0	93.4	186.8	97.9	195.8
Σ(E×F)	....	.....	1,329.1	.....	1,383.8	.....	1,296.0	.....	1,319.5
Σ(E×F)÷ΣF=Weighted average E	....	.....	94.9	.....	98.8	.....	92.6	.....	94.2

(B)—LOWER BOLTS.

Modulus of rupture	2	102.4	204.8	107.2	214.4	93.7	187.4	98.6	197.2
Modulus of elasticity	4	101.7	406.8	109.0	436.0	104.2	416.8	91.5	366.0
Work to maximum load	3	108.7	326.1	105.2	315.6	83.0	249.0	97.3	291.9
Drop	3	93.3	279.9	101.7	305.1	87.8	263.4	97.0	291.0
Compression	2	96.3	192.6	106.2	212.4	93.5	187.0	99.0	198.0
Σ(E×F)	....	.....	1,410.2	.....	1,483.5	.....	1,303.6	.....	1,344.1
Σ(E×F)÷ΣF=Weighted average E	....	.....	100.7	.....	106.0	.....	93.1	.....	96.0
Average of upper and lower bolts	....	.....	97.8	.....	102.4	.....	92.8	.....	95.1

F=Weighting factor

$$E=\text{Efficiency}=\frac{\text{Improvement ratio for property of kiln dry}}{\text{Improvement ratio for same property of corresponding air dry}}$$

DISCUSSION.

Inspection of figure 14 indicates that of the four kiln runs, 101 alone has given results which can be considered fully equal to air drying. This run falls below the corresponding air-dried material in three instances: Modulus of rupture, modulus of elasticity, and work to maximum load, all for material from upper bolts. The deficiencies in these instances are so small that they are entirely offset by superior excellence in other respects.

Further inspection shows that run 102 is very consistently, modulus of elasticity being the only exception, inferior to the corresponding air-dry, and is, upon the whole, the poorest of the four runs. These conclusions are supported by the figures presented in Table 15. Air drying is taken as the standard of efficiency, or 100 per cent. The efficiencies of air drying and of the several kiln runs, the latter as obtained by averaging the figures of Table 15 (A) with those of Table 15 (B), are as follows:

	Per cent.
Air drying	100. 0
Kiln run 101	102. 4
Kiln run 99	97. 8
Kiln run 103	95. 1
Kiln run 102	92. 7

Reference to figure 11 shows that the above list is in order of increasing temperatures; i. e., as temperature increases, efficiency decreases.

If the values for efficiency with respect to work to maximum load and maximum drop only, as given in Table 15 (A) and (B), be averaged (without weighting) we get—

	Per cent.
Air drying	100. 0
Kiln run 101	100. 6
Kiln run 99	98. 6
Kiln run 103	95. 8
Kiln run 102	86. 6

The order is as before, and the deficiency is less in runs 99 and 103, but somewhat greater in run 102.

These figures all point to a rather definite relation between strength properties and the temperatures used in drying. In no case is the deficiency sufficient to be considered an obstacle to the use of such material for ordinary purposes. However, any failure to equal air-dried material must be looked upon with considerable suspicion when stock is to be used for aircraft construction.

Tests of the effect of various steps of preservative treatment on Douglas fir have shown that this species is especially susceptible to injury by high temperatures. Data on such tests, together with those given herein, furnish the following for correlation of temperature and strength:

Temperature.[1]	Reference.	Modulus of rupture.[2]		
Degrees F.		*Per cent.*		
110	Kiln run 101	102. 3		
120	Kiln run 99	98. 0		
130	Kiln run 103	97. 8		
180	Kiln run 102	90. 5		
200	Bull. No. 286 [3]	[5] 89. 0	[6] 93. 5	[7] 91. 2
259	Bull. No. 286 [4]	[5] 78. 3	[6] 91. 7	[7] 85. 0

[1] This is the temperature applied to green wood.
[2] In percentages of control material.
[3] U. S. Department of Agriculture Bull. No. 286: Strength Tests of Structural Timbers Treated by Commercial Wood Preserving Processes. (Table 3—Creosoted at atmospheric pressure and 200 °F. for 27 hours.)
[4] Bull. No. 286: Steamed at 20-pound pressure for five hours.
[5] Bull. No. 286: Results from specimens treated green and tested soon after treatment.
[6] Bull. No. 286: Results from tests made after thorough air drying following treatment.
[7] Results of 5 and 6 averaged.

These data are plotted in figure 15. While the tests of Bulletin No. 286 are probably not exactly comparable to those described herein, they furnish basis for an estimate of the effect of still higher temperatures than those used in the kiln runs herein discussed.

The data on the four kiln runs as given in Table 15 (A) and (B) and as presented in figure 15 indicate that 120° F. is about the critical temperature for Douglas fir in the green state. The data drawn from Bulletin No. 286 by showing a continual decrease of strength properties with increase in temperature support this indication.

CONCLUSIONS.

In view of the points brought out in the above discussion these conclusions are reached: (1) There is a quite definite relation between the strength properties of Douglas fir and the temperatures used in drying it. (2) About 120° F. is the critical temperature above which damage is likely to result. (3) The decrease of strength properties with increase in temperature is gradual. (4) The maximum damage to be expected from the use of Table 1 of Specification

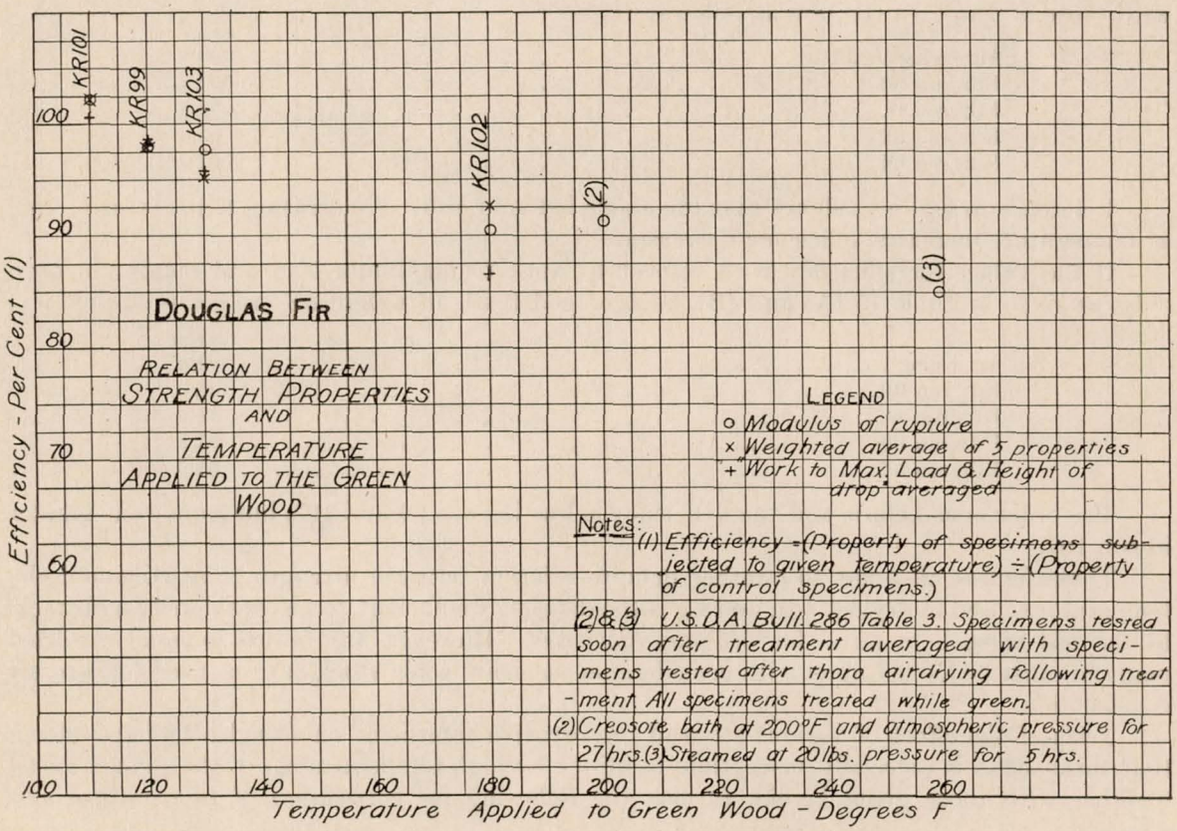


FIG. 15.—Relation between strength properties of Douglas fir and temperature applied to the green wood.

20500–A does not exceed 5 per cent. In all probability the susceptibility to damage by heat decreases as the moisture content decreases, so that even this damage is not really to be expected. (5) When maximum safety is desired, as for aircraft material, it seems doubtful if the temperature of 120° F. should be exceeded before the material is reasonably dry. (6) It is to be expected that Table 2 of Specification 20500–A will produce material fully equal to that air dried.

RECOMMENDATIONS.

It is recommended that the temperature of Table 2 of Specification 20500–A should not be exceeded in drying Douglas fir for maximum strength value. Humidities used should be such as to keep checking and casehardening to a minimum. Steaming as permitted by Specification 20500–A would be expected to have no harmful effect.

WESTERN WHITE PINE.

SOURCE OF MATERIAL.

Four experimental kiln runs have been made on material from two shipments of logs. Shipment 488, which furnished stock for kiln runs 95 and 110, consisted of logs from 24 trees cut in Idaho. These logs were 10 to 20 inches in diameter and too knotty to be considered of airplane grade. Test specimens were, however, so selected as to be unaffected by the defects and were representative of the clear wood.

Shipment 570 furnished stock for kiln runs 149 and 150. This shipment consisted of seventeen 16-foot butt logs sent to the Laboratory from Keeler, Idaho. These were of better quality than the previous shipment and were 18 to 36 inches in diameter.

Data on these two shipments are compared with data from green and air-dried material from one log of shipment 224. This shipment came from Missoula County, Mont., and was tested prior to the beginning of the present series of tests.

CUTTING OF STOCK.

The logs of shipment 488 were cut into 8-foot bolts, which were subdivided similarly to the logs of commercial white ash. (See fig. 10.) The resulting planks were cut into 2 by 3 inch, 2 by 4 inch, 2 by 5 inch, and 3 by 4 inch stock.

Table 16 shows how the material was divided for drying in two kiln runs.

The 16-foot logs of shipment 570 were sawed in a manner similar to that shown for Douglas fir in figure 1 (B). Material for test green and after air drying was derived from a 2½-inch flitch extending through the center of each log. Half of the remaining material from each log was dried in the form of 2½-inch planks, of various widths and 16 feet long.

DESCRIPTION OF KILN DRYING CONDITIONS.

Figure 16 shows graphically the kiln conditions and the moisture contents of samples of stock for the four runs 95, 110, 149, and 150.

Run 95.—The charge consisted of 2 by 3 inch, 2 by 4 inch, 2 by 5 inch, and 3 by 4 inch pieces derived from shipment 488. (See Table 16.) The arrangement of the kiln was much as for run 147 of Sitka spruce (see fig. 7), except that the material was flat piled. The piling was open (2-inch stickers and 2½ to 3 inches between the pieces in the layers), with the 2-inch stock on top of the 3-inch.

TABLE 16.—*Western white pine—Shipment 488—List of trees and bolts to show which bolts were represented in each kiln run.*

Tree and bolt.	Kiln run 95.	Kiln run 110.	Tree and bolt.	Kiln run 95.	Kiln run 110.
1 a–b		*	13 a–b		*
2 a–b	*		14 a–b	*	
2 c–d		*	14 c–d		*
3 a–b		*	15 a–b		*
4 a–b	*		16 a–b	*	
4 c–d		*	16 c–d		*
5 a–b		*	17 a–b		*
6 a–b	*		18 a–b	*	
6 c–d		*	18 c–d		*
7 a–b		*	19 a–b		*
8 a–b	*		20 a–b	*	
8 c–d		*	20 c–d		*
9 a–b		*	21 a–b		*
10 a–b	*		22 a–b	*	
10 c–d		*	22 c–d		*
11 a–b		*	23 a–b		*
12 a–b	*		24 a–b	*	
12 c–d		*	24 c–d		*

* Indicates that material from the bolt listed at the left was represented in the kiln run whose number appears at the top of the column. Material was taken from each bolt for tests in green and air-dried condition.

The run was begun with 4½ hours' preliminary steaming at 90° to 135° F. Temperatures and humidities were as shown in figure 16. The irregularities in these factors during the first few days were due to derangement of controlling apparatus. As shown by the curves of figure 16, the samples of 2-inch stock reached a satisfactory dryness and it was removed from the kiln three days ahead of the 3-inch stock.

Considerable trouble was experienced from lack of uniformity in drying. This was largely due to wide variations in the initial moisture content of different pieces and to apparently nonuniform distribution of moisture lenthwise of individual pieces.

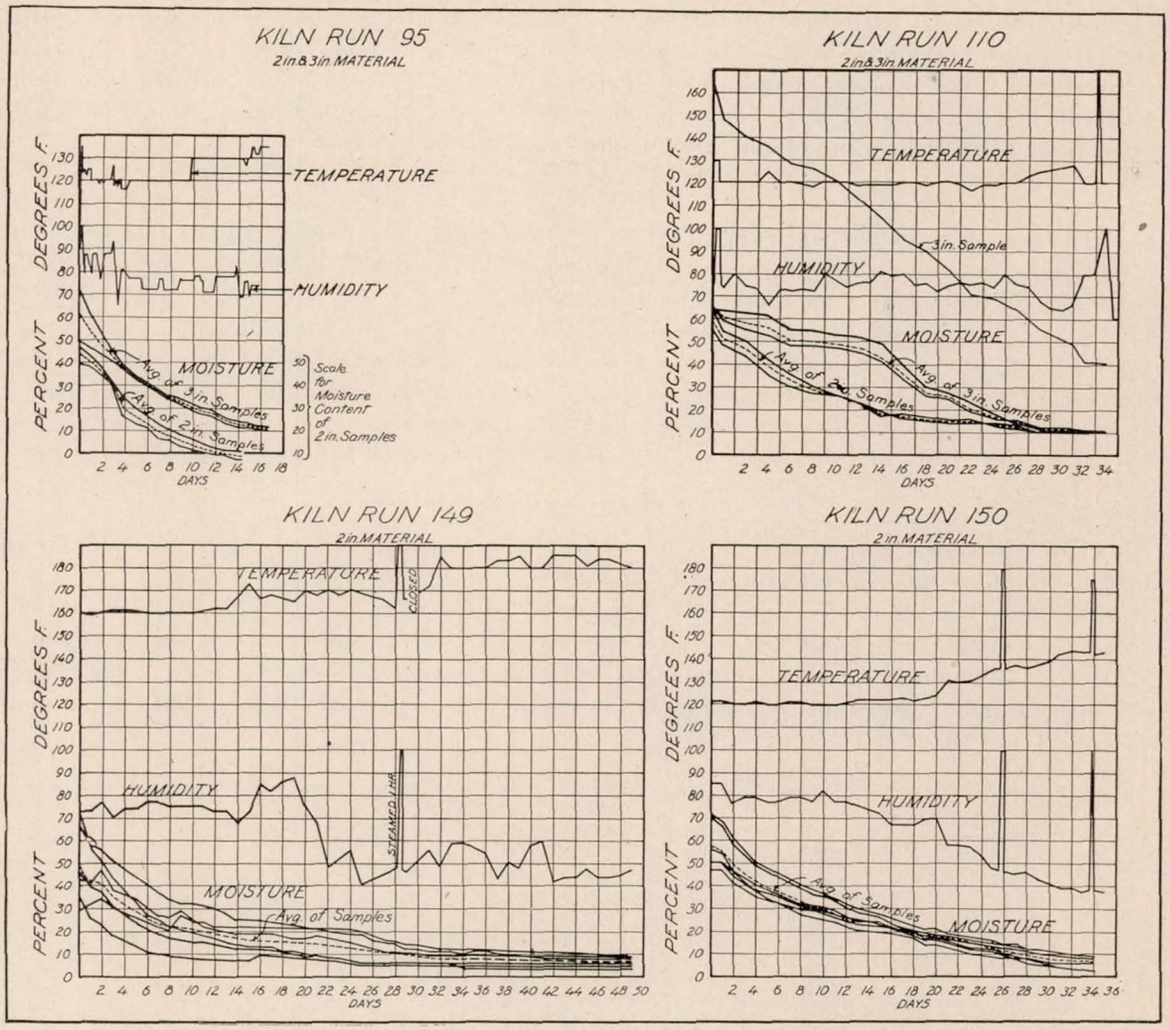


FIG. 16.—Kiln conditions for western white pine, kiln runs 95 and 110 (shipment 488) and 149 and 150 (shipment 570).

Some slight evidence of casehardening was found near the end of the run. It was not sufficient, however, to necessitate steaming.

Run 110.—The charge for this run, as for 95, was of 2 by 3 inch, 2 by 4 inch, 2 by 5 inch, and 3 by 4 inch pieces derived from shipment 488 (see Table 16). Arrangement of the kiln and piling of stock was quite similar to run 95. Spaces between pieces in the layers were, however, only one-half to three-fourths of an inch.

After preliminary steaming at 135° F. for 18 hours, drying conditions were established and continued as shown by figure 16. As in run 95, considerable trouble was experienced because of nonuniformity of moisture distribution in the charge. This condition obtained both at the beginning and at the end of the run. The closer piling was perhaps in part responsible for the longer drying period than in run 95. Furthermore, because of the very high moisture

content of one sample, raising of temperature and lowering of humidity were delayed longer than in run 95.

Run 149.—The charge consisted of 3 by 3 inch, 3 by 5 inch, and 3 by 8 inch pieces, 16 feet in length, derived from shipment 570. Material was flat piled on 1½-inch stickers with 2-inch spaces.

The very long time required for this run is due largely to the fact that it was made in an experimental kiln in which a fan circulatory system had been devised and which had not yet been rendered controllable. Circulation was very poor and resulted in nonuniformity of temperature between different parts of the kiln. Slight casehardening was relieved by steaming for one hour at 185° F. on the thirtieth day. No casehardening was evident at the close of the run.

Run 150.—The charge consisted of 3 by 3 inch, 3 by 4 inch, and 3 by 5 inch pieces, 16 feet in length and of various widths, derived from shipment 570. The material was close-piled on a slant, with 1½-inch stickers. Material was steamed for one hour on two occasions at 180° and 174° F., respectively, to relieve casehardening. Slight casehardening was present when the material was removed from the kiln.

AIR DRYING.

Material was stored for air drying under conditions similar to those for Sitka spruce and Douglas fir, as previously described.

STRENGTH DATA.

Table 17 gives the complete data available after the testing of the air-dried material Improvement ratios derived from this table are shown in Table 18 and graphed in figure 17.

TABLE 17.—*Average mechanical test values of western white pine—(Tabulations as tested—No adjustment for moisture content).*

Property.	Shipment 224.		Shipment 488.						Shipment 570.			
	Green.	Air dry.	Green, to match kiln run 95.	Air dry, to match kiln run 95.	Kiln run 95.	Green, to match kiln run 110.	Air dry, to match kiln run 110.	Kiln run 110.	Green, to match kiln run 149.	Kiln run 149.	Green, to match kiln run 150.	Kiln run 150.
STATIC BENDING.												
Moisture (per cent)[1]	47.9	8.0	65.9	11.6	11.0	57.3	12.0	8.0	46.4	7.9	45.7	8.5
Specific gravity[2]	.405	8.414	.360	.397	.388	.372	.400	.403	.347	.390	.345	.386
Fiber stress at elastic limit (lbs. per sq. in.)	3,961	12,938	3,400	6,360	6,610	3,600	6,270	8,500	3,280	7,560	3,240	7,310
Modulus of rupture (lbs. per sq. in.)	6,147	1,356	5,130	9,420	10,000	5,410	9,200	11,330	5,160	11,480	5,100	10,600
Modulus of elasticity (1,000 lbs. per sq. in.)	1,210	,468	1,132	1,486	1,512	1,112	1,471	1,719	1,169	1,623	1,149	1,523
Work to elastic limit (inch-lbs. per cu. in.)	.73	2.9	6.2	1.5	1.6	6.7	1.5	2.4	.6	2.2	5.3	2.0
Work to maximum load (inch-lbs. per cu. in.)	5.5	10.7	4.6	7.9	7.5	5.2	7.6	7.7	5.4	9.3	5.3	9.2
IMPACT BENDING, 50-POUND HAMMER.												
Moisture (per cent)[1]	46.1	8.3	64.5	11.1	11.8	59.4	11.8	9.9	45.5	7.7	45.6	10.5
Specific gravity[2]	.362	15.402	.362	.385	.379	.366	.396	.399	.361	.383	.358	.388
Fiber stress at elastic limit (lbs. per sq. in.)	7,218	1,070	7,650	11,900	12,160	7,150	11,250	12,730	7,980	11,640	7,930	11,120
Modulus of elasticity (1,000 lbs. per sq. in.)	1,221	,967	1,364	1,756	1,860	1,324	1,678	2,099	1,403	1,765	1,402	1,701
Work to elastic limit (inch-lbs. per cu. in.)	.....	.....	2.5	4.6	4.5	2.2	4.2	4.3	2.6	4.3	2.6	4.0
Drop causing complete failure (inches)	17.0	25.0	17.4	19.6	20.3	16.4	21.3	24.0	17.6	25.6	17.6	23.9
COMPRESSION PARALLEL TO GRAIN.												
Moisture (per cent)[1]	58.2	7.9	55.0	11.7	12.0	62.1	12.1	6.6	47.1	7.8	47.1	8.2
Specific gravity[2]	.393	7.432	.360	.389	.379	.362	.389	.394	.350	.385	.350	.382
Maximum crushing strength (lbs. per sq. in.)	3,070	,840	2,540	5,120	5,630	2,470	5,190	7,690	2,390	5,750	2,390	6,000

[1] *Per cent moisture based on oven-dry weight.* [2] Specific gravity based on oven-dry weight and volume as tested

TABLE 18.—*Average improvement ratios of western white pine.—(With and without adjustment to 9 per cent moisture.)*

Shipment.	Seasoning.	Static bending.							Impact bending, 50-pound hammer.			Compression parallel to grain.		
		Moisture.	Modulus of rupture.		Modulus of elasticity.		Work to maximum load.		Moisture.	Height of maximum drop.		Moisture.	Maximum crushing strength.	
			I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.
		Per ct.							*Per ct.*			*Per ct.*		
224	Air-dry	8.0	2.01	1.87	1.21	1.19	1.95	1.81	8.3	1.47	1.42	7.9	2.55	2.30
488	Air-dry	11.6	1.84	2.01	1.31	1.37	1.72	1.87	11.1	1.13	1.14	11.7	2.02	2.26
	Kiln run 95	11.0	1.95	2.08	1.34	1.38	1.63	1.71	11.8	1.17	1.20	12.0	2.22	2.58
488	Air-dry	12.0	1.70	1.88	1.32	1.40	1.46	1.57	11.8	1.30	1.36	12.1	2.10	2.44
	Kiln run 110	8.0	2.09	1.94	1.55	1.48	1.48	1.42	9.9	1.46	1.47	6.6	3.11	2.54
570	Kiln run 149	7.9	2.23	2.03	1.39	1.34	1.72	1.62	7.7	1.46	1.39	7.8	2.41	2.17
570	Kiln run 150	8.5	2.08	1.97	1.33	1.30	1.74	1.67	10.5	1.36	1.38	8.2	2.51	2.40

Fiber-saturation point assumed to be at 24 per cent moisture content. I. R.=Improvement ratio.

In Table 19 and in figure 18 are given the ratios which were available for the first analysis. These ratios differ slightly from those in Table 18 and figure 17 because when Table 18 was

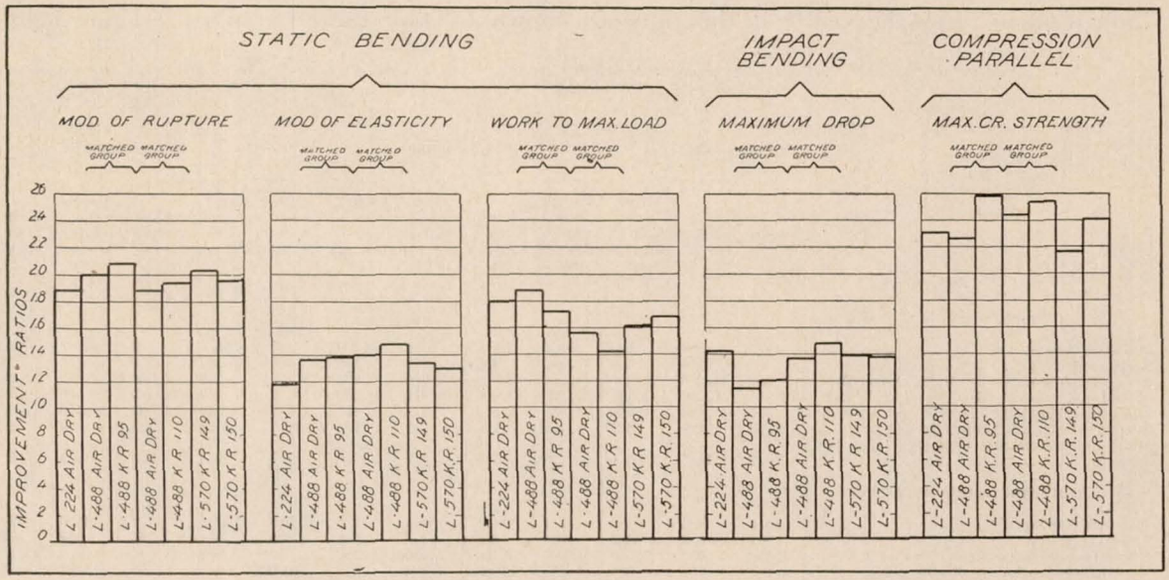


FIG. 17.—Improvement ratios for comparison of groups of kiln and air dried stock, western white pine.

made up it became necessary, in order to secure the best matching, to reject some specimens, results from which had been used in making up Table 19.

TABLE 19.—*Average improvement ratios of western white pine.—(With and without adjustment to 9 per cent moisture.)*

[Shipments 224 and 448.]

Seasoning.	Static bending.							Impact bending, 50-pound hammer.			Compression parallel to grain.		
	Moisture.	Modulus of rupture.		Modulus of elasticity.		Work to maximum load.		Moisture.	Height of maximum drop.		Moisture.	Maximum crushing strength.	
		I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.
	Per ct.							*Per ct.*			*Per ct.*		
Air-dry[1]	8.0	2.01	1.93	1.21	1.19	1.95	1.87	8.3	1.47	1.45	7.9	2.55	2.39
Kiln run 95	10.9	1.96	2.16	1.35	1.41	1.64	1.76	11.6	1.32	1.40	12.0	2.24	2.74
Kiln run 110	8.0	2.09	2.00	1.55	1.51	1.53	1.49	8.0	1.42	1.39	6.6	3.12	2.66

[1] Air-dried material from shipment 224. I. R.=Improvement ratio.

DISCUSSION AND CONCLUSIONS.

As mentioned on page 20, western white pine is to be used as an example of the two methods of analysis:

1. First or preliminary analysis based on comparison of kiln-dried and previously air-dried material by means of the increase in strength properties produced by kiln drying as compared to the previously observed increase from air drying.
2. Second analysis based on comparisons of matched kiln and air-dried material.

FIRST ANALYSIS.

As the example of this first analysis, the discussion, conclusions, and recommendations substantially as given in a report made when the data of Table 19 and figure 18 only were available will be repeated here.

Discussion.—Figure 18 shows that the improvement in strength properties produced by kiln drying, with the exception of work to maximum load, is practically as great as is secured by air drying as determined by previous tests from a single tree.

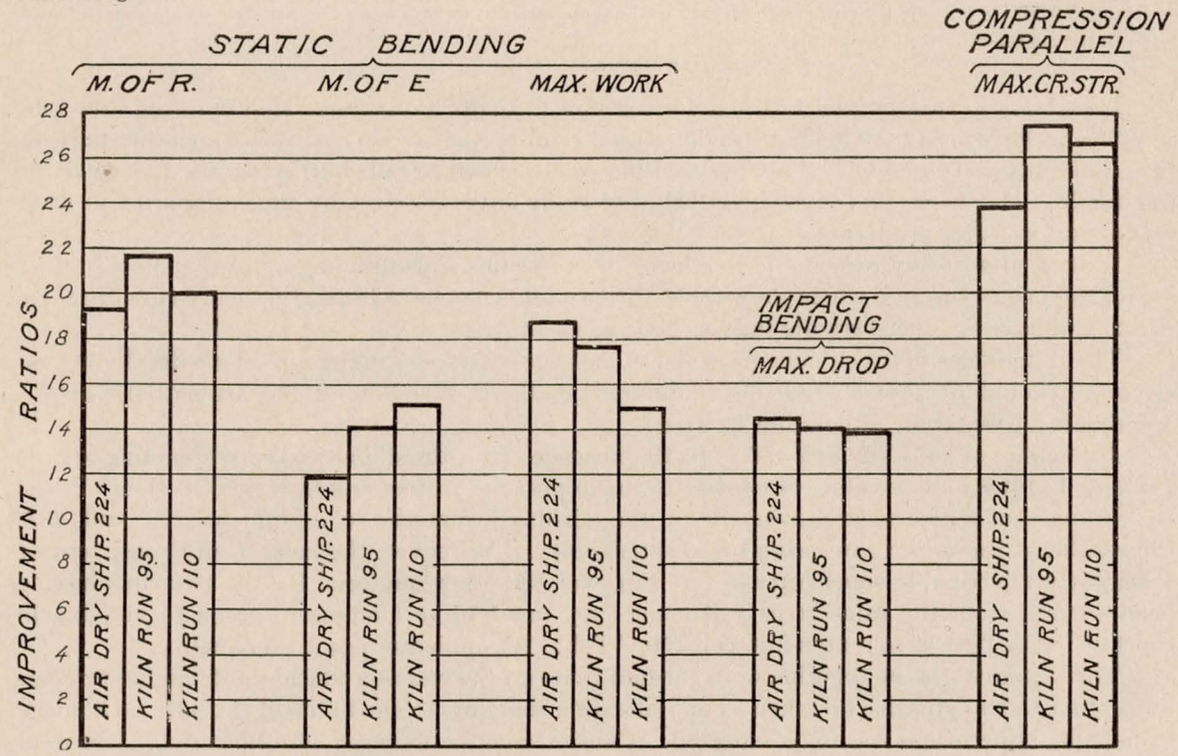


FIG. 18.—Improvement ratios for comparison of kiln runs 95 and 100 with air-dried stock of a previous shipment (shipment 224), western white pine.

Apparently air drying produced in the material of this one tree exceptional improvement in work to maximum load. This belief is supported by the fact that in most if not all cases other coniferous woods have shown less increase in this property. Also the actual values for work to maximum load for the air-dried material of this one tree is higher than for any other coniferous species except the very heavy and dense ones, such as longleaf pine. Furthermore, it is the general, but not invariable, rule that deflection to maximum load should decrease in air drying. Data on deflections to maximum load are given in Table 20.

TABLE 20.—*Average deflections to maximum load with and without adjustments.*

	Air-dry shipment 224.	Kiln run 95.	Kiln run 110.
Deflection of green sticks to match ..... inches..	0.73	0.73	0.70
Deflection of seasoned sticks ..... inches..	.75	.73	.68
Size of seasoned sticks ..... inches..	2 by 2	1.75 by 1.75	1.75 by 1.75
Deflection of seasoned material—adjusted for size of sticks ..... inches..	.75	.64	.60
Improvement ratio of deflection [1]	1.03	.85	.85

[1] Adjusted for size of stick and moisture content. All green sticks were 2 by 2 inches.

From the foregoing it is concluded that the increase in work to maximum load obtained from the one tree previously air dried is abnormal and that the improvement of the kiln-dried material in this respect has probably been as great as would have resulted had the same material been air dried.

Conclusions.—It is concluded, then, that in all probability runs 95 and 110 have produced as good results as would have resulted from air drying the same material. The conditions in these runs were less severe than permitted by Specification 20500–A in that the specification admits of lower humidities than were used near the end of the run. However, the high humidities maintained until the end of the runs (in 110 because of the very high moisture content of a single sample) are not believed essential to the preservation of strength properties. A lower humidity would perhaps have shortened the time of drying somewhat. Data on material dried in accordance with Specification 20500–A are not yet available.

The difficulty experienced in these runs through large variations in moisture content of the stock, and through drying two thicknesses together, emphasizes the desirability of classifying material on the basis of moisture content and size, and of drying each class separately. A rough moisture classification such as could be obtained by "hefting" each piece as loaded into the kiln would probably expedite the drying.

Recommendations.—It is recommended:

1. That, until additional data on the effect of various temperatures and humidities on the strength of western white pine can be obtained, Table 1 of Specification 20500–A be used for drying this species.

2. That consideration be given to grouping material into two or more classes on the basis of moisture content, and to drying material of but one moisture content class in the same kiln charge or placing the material containing the most water in the fastest-drying portion of the kiln.

SECOND ANALYSIS.

Discussion of runs 95 and 110.—Referring now to figure 17, it is seen that material from kiln runs 95 and 110 excels matched air-dried material in all properties except work to maximum load. This is the property in which the kiln-dried material seemed to fall short when the first analysis was made. However, this shortage is believed to be entirely offset by the superiority in drop values and in other properties.

In fact, almost any reasonable weighting of properties and summing up of the effect of drying on the properties as a whole shows that the two kiln runs have been practically equal in their effect, and have produced results fully as good as air drying.

The differences between runs 95 and 110 and the corresponding groups of air-dried material are in all probability not a result of the different methods of seasoning, but are actual inherent differences in material, impossible to avoid.

Discussion of runs 149 and 150.—In the absence of air-dried material corresponding to runs 149 and 150 it is not possible, of course, to make positive statements in regard to their effects. By comparison with the improvement in the air-dried material of shipment 224 and 488, the results of these two runs seem quite satisfactory. Moreover, the lack of any consistent or apparently appreciable superiority of one run over the other, material for the two runs having been secured from the same trees and being very much alike (compare "green to match kiln run 149" with "green to match kiln run 150," Table 17), indicates practical equality.

This equality, taken together with the fact that run 149 was at a considerably higher temperature than 150, might also be taken as an indication that, up to the limits of run 149, no damage from high temperatures was to be expected. Caution must be observed here, however. It is indicated by the long period required for drying in run 149, and also shown by records of this run, that circulation was not good. The natural accompaniment of poor circulation is nonuniformity of temperatures in different parts of the kiln. Hence it is entirely possible that some of the material tested may not have been subjected to as severe temperature conditions as are indicated in figure 16.

It must be said that, in general, the kiln drying of western white pine in these runs has not been eminently satisfactory. This is attributed largely to the character of the material with respect to moisture content. As has been mentioned, moisture content has been found to be very nonuniform.

Conclusions.—It is believed that the data presented herein justify the following conclusions:

1. Western white pine can be kiln dried without damage to strength properties.

2. Table 1 of Specification 20500–A can be depended on to dry western white pine without damage to strength properties.

Recommendations.—It is recommended that, pending the results of further tests, the temperatures of Specification 20500–A be not exceeded in drying western white pine, and that the humidity and steaming be regulated to keep casehardening to a minimum.

COMMERCIAL WHITE ASH.[1]

Eight kiln runs (81, 82, 83, 90, 96, 97, 92, and 100) have been made on white ash to show the effect of drying under various combinations of temperatures and humidities.

SOURCE OF MATERIAL.

Shipment 499 consisted of partially air-dried rough planks furnished by one of the airplane companies. This furnished material for runs 81, 82, and 83, which included both ash and Sitka spruce and are previously mentioned as "preliminary runs."

Shipment 505 consisted of one log from each of 33 trees from southeastern Arkansas. Three logs were 12 feet long and the remainder 16 feet. Top diameters ranged from 13 to 23 inches and the average total taper from top to butt of log was 6½ inches.

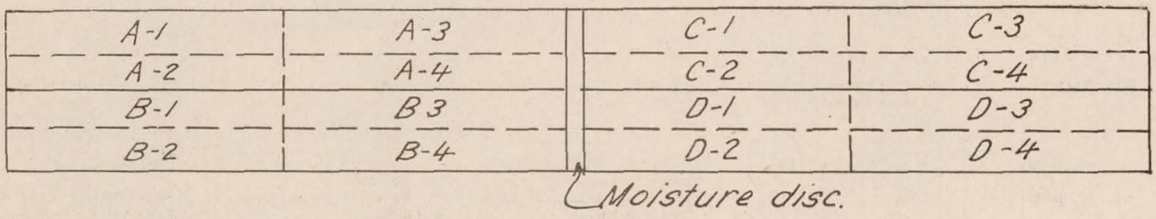


FIG. 19.—Cutting of white ash planks, shipment 499.

Material from logs 1 to 12, inclusive, was dried in run 90. Logs 13 to 33, inclusive, were represented in each of the runs 96 and 97. Mechanical test specimens for runs 96 and 97 were derived from material from the even-numbered logs.

Shipment 507 consisted of fifty 12-foot logs from near Goshen, Ind. Top diameters ranged from 11 to 19 inches and the average total taper was 2½ inches. Material for runs 92 and 100 was derived from this shipment.

MARKING AND MATCHING.

The material from shipments 505 and 507 was cut from the logs as illustrated in figure 10, and was marked and matched in the usual manner, as previously described.

Material for runs 81 and 82 was derived from 10 planks of shipment 499, cut and numbered as shown in figure 19. Pieces marked "D" were dried in run 81 and those numbered "A"

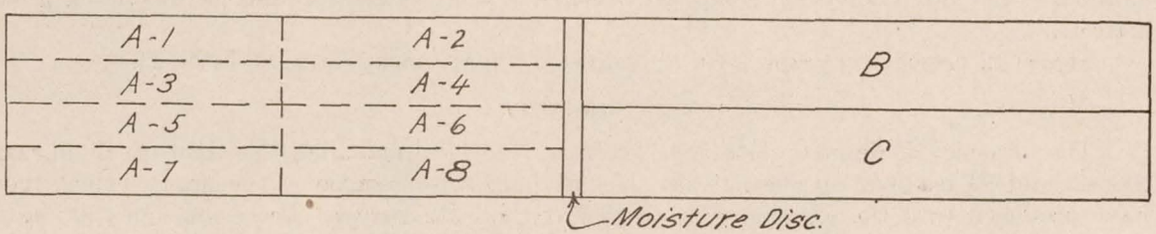


FIG. 20.—Cutting of white ash planks, shipment 499.

in run 82. Sticks A–1, A–4, D–1, and D–4 were tested as dried; A–2, A–3, and D–2, and D–3 were steamed and bent after kiln drying;[2] B–1, B–4, C–1, and C–4 were tested partially air-dried, or as received at the laboratory; and B–2, B–3, C–2, and C–3 were stored for complete air drying.[3]

In grouping data for the analysis of the effect of kiln drying on strength, A sticks were considered as matched to C, and D to B.

The material for run 83 was taken from 20 planks of shipment 499, cut as shown in figure 20. Piece A was kiln dried and tested, and pieces B and C were tested after air drying for about 11 months.

[1] The white ash tested was not identified as to exact species. It was, however, of some of the species included in the term "commercial white ash," the most important of which are: White ash (*Fraxinus americana*), green ash (*Fraxinus lanceolata*), blue ash (*Fraxinus quadrangulata*), biltmore ash (*Fraxinus biltmoreana*).

[2] The results of the steaming and bending tests are not to be discussed here.

[3] These sticks have not been tested.

DESCRIPTION OF KILN DRYING CONDITIONS.

Quantity and sizes of stock, method of piling, and condition before and after drying are given for each kiln run in Table 21. Figure 21 shows the drying conditions for each run. Steaming to relieve casehardening was done in runs 82 and 90 and is indicated on the diagrams (fig. 21) by a sudden high humidity held for a short time near the end of the run. Initial steaming was used in runs 90, 92, and 96.

TABLE 21.—*Description of commercial white ash dried in kiln runs 81, 82, 83, 90, 96, 97, 92, and 100.*

Run.	Amount of stock.	Size of pieces.	Piling.	Condition on entering the kiln.	Condition when taken from kiln.
81	10 planks	1¼-inch planks, various widths.	Open—flat	Partially air dry; good condition except very badly weather stained.	No visible harm.
82	do	do	do	do	Do.
83	20 planks	do	do	Partially air dry; slight checks.	O. K.
90	71 planks	2-inch planks, various widths, 16 feet long.	Close—flat, 1¾-inch stickers every 2 feet.	Good condition	Less than ½ per cent degrade, all being in 7 planks, 6 of which were checked and 1 cupped; no signs of casehardening.
96	183 pieces	2 by 2 inches by 16 feet	Open—flat, 1¾-inch stickers every 2½ feet.	Badly sprung and in some cases checked.	No visible degrade.
97	202 pieces	do	Open—flat, 2-inch stickers every 2½ feet.	Very badly sprung and checked.	No visible degrade; most of warping was eliminated.
92	282 pieces	2 by 2 inches, 10, 12, and 16 feet long.	Open—flat, 1½-inch stickers every 2 feet.	Badly warped, twisted, and checked.	No visible degrade; twisted and bent condition considerably relieved.
100	253 pieces	2 by 2 inches by 14 feet	Open—flat, 1¾-inch stickers, 2-inch chimneys.	Good condition	No degrade.

AIR DRYING.

Material was air dried under conditions similar to those previously described for Sitka spruce and Douglas fir.

STRENGTH DATA.

Average strength values for the various groups of material are given in Table 22.

Table 23 gives the improvement ratios for the more important properties of the air-dried material and for that dried in the various kiln runs, both without adjustment and after adjustment to 10 per cent moisture. Each ratio given in this table is based on the average of all the material of any kiln or air dried group, as compared to the average from the corresponding green material.

Figure 22 presents in graph form the adjusted improvement ratios of Table 23.

DISCUSSION.

The absence of complete data, i. e., green and air-dried matching that kiln dried, on runs 81, 82, and 83 makes it necessary that they be judged by comparing the improvement they have produced with that produced in air drying the *other groups*. Proceeding on this basis, it is seen that 83 is normal or above normal in all respects, while 81 and 82 are quite low in work to maximum load, and 82 is very low in drop. (See Table 22 and fig. 22.) It is concluded that 83 has in all probability produced as good results as would be secured from air drying, but that 81 and 82 have failed to give good results in work and drop values which are measures of shock-absorbing ability and of great importance in airplane material.

Careful scrutiny of Tables 22 and 23 and figure 22 shows that runs 90, 96, 97, 92, and 100 are all fully equal to the corresponding air-dried material in the important properties "work to maximum load" and "drop"; that all except 90 are equal or superior to air-dried in modulus of elasticity; and that 96 only is fully equal to the air-dried in modulus of rupture and maximum crushing strength. Furthermore, run 90 falls very considerably below air dried in these latter properties. A résumé of the above amounts to this:

1. That the apparent "efficiency" of the kiln drying as shown in figure 22 and Table 24 is greatest for those properties which are least affected by changes of moisture content—work to maximum load, drop, and modulus of elasticity—and least for those properties which are most influenced by changes of moisture content—modulus of rupture and maximum crushing strength.

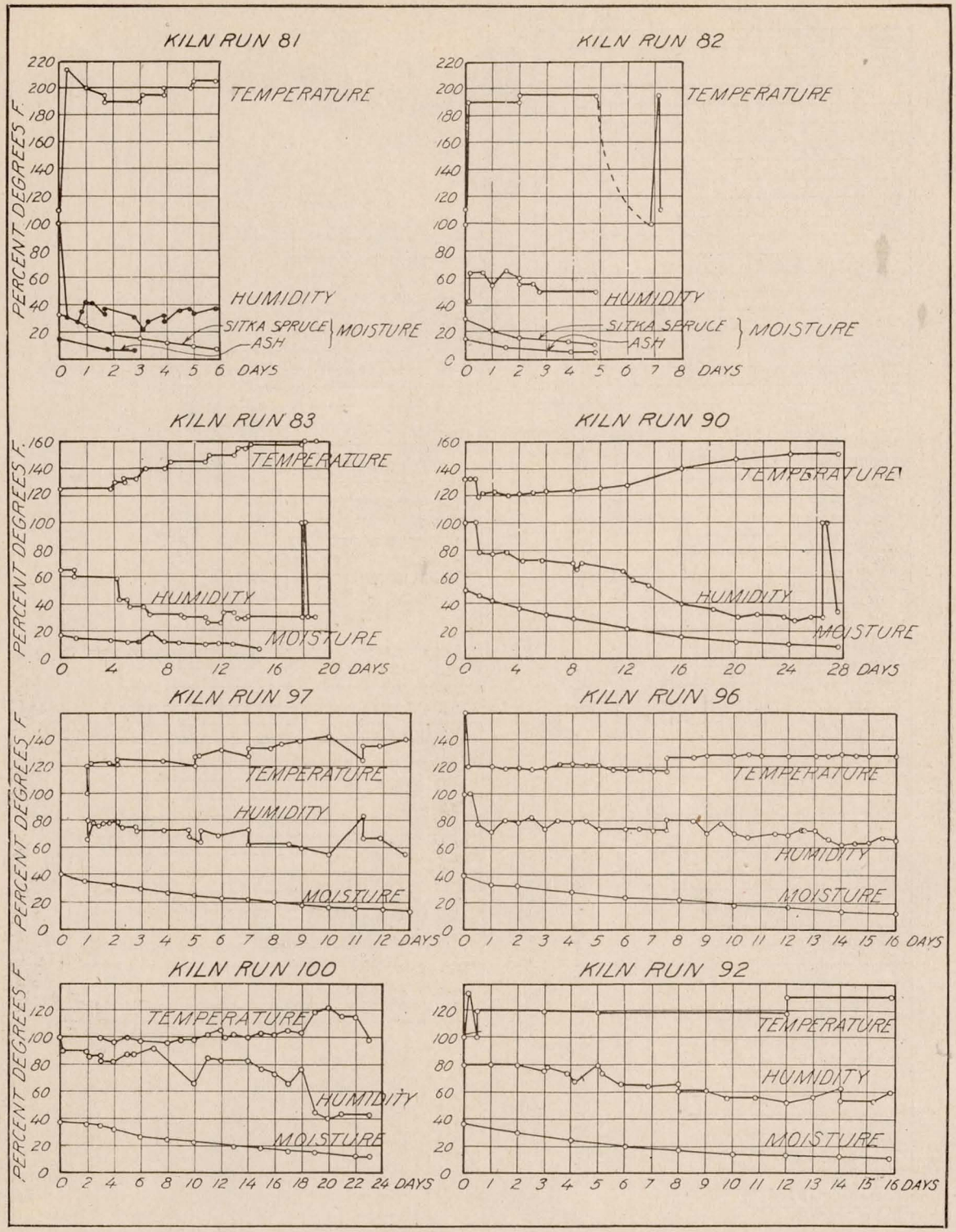


FIG. 21.—Kiln conditions for white ash kiln runs 81, 82, and 83 (shipment 499), runs 90, 96, and 97 (shipment 505), and runs 92 and 100 (shipment 507).

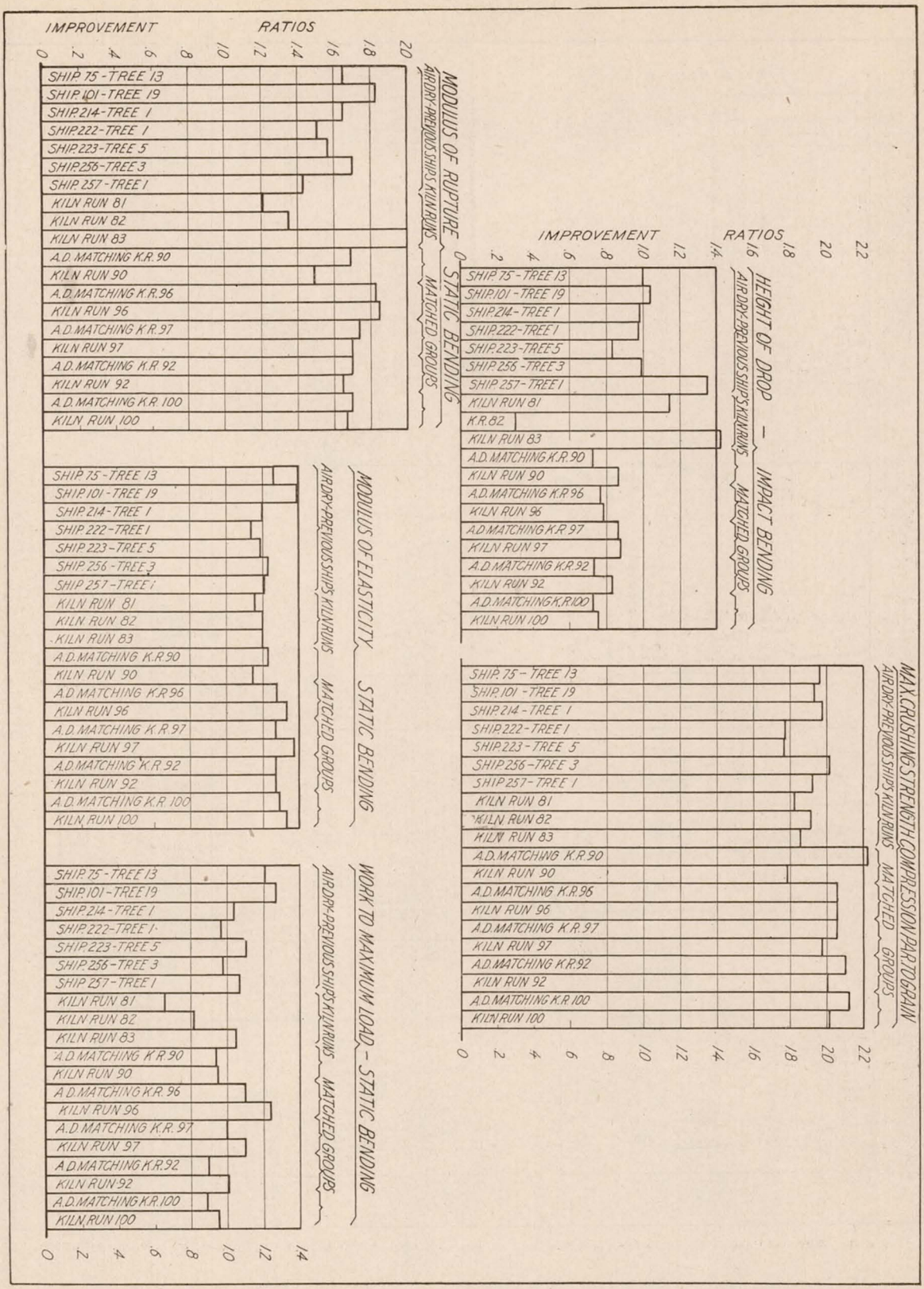


FIG. 22.—Improvement ratios adjusted to 10 per cent moisture for comparing ten kiln runs on commercial white ash.

2. That the run (90) showing the lowest apparent efficiency in modulus of rupture and maximum crushing strength is the run in which moisture content of the kiln-dried material is farthest below the corresponding air-dried material; consequently, for which adjustment of moisture had to be made across the widest interval.

Now it is recognized that the methods of moisture adjustment, while the best that it has been possible to devise, are not perfect, and it can be demonstrated that any errors in the applicability of the fundamental assumptions underlying the methods of adjustment used will have the largest *percentage* effect on the computed "efficiencies" as presented in Table 24, when:

1. Applied to those properties which are most largely affected by change of moisture content.

2. The interval across which moisture adjustment must be made is largest.

TABLE 22.—*Mechanical properties of commercial white ash (summaries of original test values).*

	Various shipments.		Shipment 499.					Shipment 505.			
	Tree. 13 19 1 1 5 3 1	Ship. 75 101 214 222 223 256 257	Partially air-dry matching kiln runs 81–82.	Kiln run 81.	Kiln run 82.	Air-dry matching kiln run 83.	Kiln run 83.	Green matching kiln run 90.	Air-dry matching kiln run 90.	Kiln run 90.	Green matching kiln run 96.
	Green.	Air-dry.									
STATIC BENDING.											
Moisture (per cent)[1]	41.0	8.9	15.9	4.4	7.2	12.6	6.2	45.1	12.9	8.9	42.4
Specific gravity[2]	.54	.597	.558	.578	.602	.568	.588	.534	.574	.586	.519
Fiber stress at elastic limit (lbs. per sq. in.)	5,750	11,060	6,280	8,560	9,300	7,280	10,340	5,460	8,320	8,110	4,910
Modulus of rupture (lbs. per sq. in.)	10,050	16,940	10,940	13,460	14,250	12,440	16,530	8,940	12,970	13,970	8,520
Modulus of elasticity (1,000 lbs. per sq. in.)	1,509	1,900	1,437	1,689	1,676	1,569	1,748	1,349	1,563	1,613	1,266
Work to elastic limit (inch-lbs. per cu. in.)	1.26	3.64	1.55	2.52	2.97	1.95	3.46	1.30	2.49	2.32	1.10
Work to maximum load (inch-lbs. per cu. in.)	14.29	15.4	13.40	8.34	11.2	13.3	13.5	13.0	12.51	12.2	12.20
Work, total (inch-lbs. per cu. in.)	40.29	30.5	21.0	1.9	18.3	.....	23.2	.....	.....	.....	.....
IMPACT BENDING, 50-POUND HAMMER.											
Moisture (per cent)[1]	41.6	8.7	17.0	4.8	7.2	13.5	6.0	44.4	12.8	8.8	41.0
Specific gravity[2]	.534	.592	.560	.581	.586	.556	.599	.542	.587	.596	.527
Fiber stress at elastic limit (lbs. per sq. in.)	12,280	19,500	15,290	17,750	15,510	19,120	21,750	13,030	13,880	13,200	10,020
Modulus of elasticity (1,000 lbs. per sq. in.)	1,605	2,189	2,151	2,708	2,616	3,066	2,697	1,848	2,254	2,026	1,605
Work to elastic limit (inch-lbs. per cu. in.)	5.25	9.77	6.1	6.5	5.4	6.8	9.9	5.1	4.7	4.8	3.5
Drop causing complete failure (inches)	38.7	39.0	32.4	37.8	10.1	38.0	48.1	43.1	34.1	36.0	43.6
COMPRESSION PARALLEL TO GRAIN.											
Moisture (per cent)[1]	42.2	9.0	16.5	4.7	7.4	11.7	6.9	45.8	12.5	9.0	43.5
Specific gravity[2]	.541	.597	.558	.586	.591	.585	.592	.531	.578	.590	.518
Maximum crushing strength (lbs. per sq. in.)	4,310	8,760	4,650	9,380	8,380	6,530	8,880	3,730	6,800	6,990	3,780
COMPRESSION PERPENDICULAR TO GRAIN.											
Crushing strength at elastic limit (lbs. per sq. in.)	855	1,772	.....	.....	.....	.....	.....	865	1,546	1,567	828
HARDNESS, BALL TEST.											
End (pounds)	1,033	1,964	1,171	1,410	2,118	.....	1,919	954	1,628	1,691	1,006
Radial (pounds)	952	1,422	1,026	1,305	1,377	.....	1,441	860	1,278	1,292	909
Tangential (pounds)	984	1,398	1,080	1,248	1,440	.....	1,453	889	1,250	1,358	940
SHEARING STRENGTH.											
Radial (lbs. per sq. in.)	1,299	2,106	.....	.....	.....	.....	.....	1,364	1,920	2,036	1,286
Tangential (lbs. per sq. in.)	1,284	2,028	.....	.....	.....	.....	.....	1,316	1,774	1,966	1,262
TENSION PERPENDICULAR TO GRAIN.											
Radial (lbs. per sq. in.)	551	810	.....	.....	.....	.....	.....	.....	934	.....	608
Tangential (lbs. per sq. in.)	679	789	.....	.....	.....	.....	.....	.....	677	.....	561
CLEAVAGE.											
Radial (lbs. per inch of width)	330	457	.....	.....	.....	.....	.....	.....	433	.....	329
Tangential (lbs. per inch of width)	376	248	.....	.....	.....	.....	.....	.....	415	.....	309

TABLE 22.—*Mechanical properties of commercial white ash*—Continued.

	Shipment 505—Continued.					Shipment 507.					
	Air-dry matching kiln run 96.	Kiln run 96.	Green matching kiln run 97.	Air-dry matching kiln run 97.	Kiln run 97.	Green matching kiln run 92.	Air-dry matching kiln run 92.	Kiln run 92.	Green matching kiln run 100.	Air-dry matching kiln run 100.	Kiln run 100.
STATIC BENDING.											
Moisture (per cent)[1]	13.0	12.2	42.1	13.0	12.9	35.8	12.7	11.0	36.0	12.6	11.3
Specific gravity[2]	.577	.566	.525	.579	.596	.565	.599	.619	.561	.598	.612
Fiber stress at elastic limit (lbs. per sq. in.)	7,720	7,640	5,110	7,870	7,210	5,770	9,390	8,800	5,680	9,340	9,240
Modulus of rupture (lbs. per sq. in.)	12,940	13,780	8,820	12,930	12,850	9,750	14,340	15,280	9,660	14,280	15,020
Modulus of elasticity (1,000 lbs. per sq. in.)	1,502	1,583	1,294	1,526	1,613	1,452	1,729	1,796	1,429	1,736	1,833
Work to elastic limit (inch-lbs. per cu. in.)	2.17	2.10	1.17	2.24	1.86	1.30	2.94	2.44	1.28	2.96	2.63
Work to maximum load (inch-lbs. per cu. in.)	13.0	14.45	12.75	12.77	13.6	16.32	15.12	16.50	16.47	15.03	15.9
Work, total (inch-lbs. per cu. in.)	.....	41.6	.....	.....	.....	.....	.....	.....	.....	.....	.....
IMPACT BENDING, 50-POUND HAMMER.											
Moisture (per cent)[1]	13.4	11.9	40.2	13.2	11.9	36.7	12.6	11.1	36.7	12.7	11.2
Specific gravity[2]	.567	.582	.529	.572	.570	.579	.604	.617	.567	.604	.608
Fiber stress at elastic limit (lbs. per sq. in.)	12,280	12,110	10,170	12,540	12,100	12,830	16,340	13,480	12,700	16,350	13,310
Modulus of elasticity (1,000 lbs. per sq. in.)	2,015	2,176	1,590	2,082	1,995	1,910	2,145	2,334	1,876	2,165	2,281
Work to elastic limit (inch-lbs. per cu. in.)	4.2	3.8	3.7	4.2	3.9	4.8	7.0	4.5	4.8	7.0	4.4
Drop causing complete failure (inches)	36.4	35.8	40.6	36.7	36.1	52.6	41.7	44.5	53.3	42.2	41.3
COMPRESSION PARALLEL TO GRAIN.											
Moisture (per cent)[1]	12.9	12.0	43.5	12.9	12.6	37.0	12.8	11.0	36.9	12.8	11.0
Specific gravity[2]	.570	.572	.518	.570	.569	.565	.611	.626	.553	.610	.605
Maximum crushing strength (lbs. per sq. in.)	6,260	6,660	3,780	6,260	6,240	3,950	6,770	7,380	3,920	6,750	7,310
COMPRESSION PERPENDICULAR TO GRAIN.											
Crushing strength at elastic limit (lbs. per sq. in.)	1,465	1,490	828	1,465	1,196	904	1,641	1,642	904	1,641	1,630
HARDNESS, BALL TEST.											
End (pounds)	1,430	1,469	1,006	1,430	1,464	978	1,651	1,753	975	1,648	1,914
Radial (pounds)	1,191	1,232	909	1,191	1,164	950	1,288	1,299	944	1,293	1,425
Tangential (pounds)	1,398	1,245	940	1,398	1,226	981	1,382	1,364	981	1,375	1,505
SHEARING STRENGTH.											
Radial (lbs. per sq. in.)	2,110	2,079	1,286	2,110	1,911	1,363	2,254	2,053	1,363	2,254	2,151
Tangential (lbs. per sq. in.)	1,876	1,882	1,262	1,876	1,820	1,363	2,083	2,021	1,363	2,083	2,085
TENSION PERPENDICULAR TO GRAIN.											
Radial (lbs. per sq. in.)	736	.....	608	736	.....	.....	.....	.....	.....	.....	.....
Tangential (lbs. per sq. in.)	838	.....	561	838	.....	.....	.....	.....	.....	.....	.....
CLEAVAGE.											
Radial (lbs. per inch in width)	446	.....	329	446	.....	.....	.....	.....	.....	.....	.....
Tangential (lbs. per inch of width)	341	.....	309	341	.....	.....	.....	.....	.....	.....	.....

[1] Per cent moisture based on oven-dry weight.

[2] Specific gravity based on oven-dry weight and volume at test.

NOTES:

Shipment 75—Green ash (*Fraxinus lanceolata*) grown in Richland Parish, La.
Shipment 101—White ash (*Fraxinus americana*) grown in Stone County, Ark.
Shipment 214—White ash (*Fraxinus americana*) grown in Oswego County, N. Y.
Shipment 222—Blue ash (*Fraxinus quadrangulata*) grown in Bourbon County, Ky.
Shipment 223—Green ash (*Fraxinus lanceolata*) grown in New Madrid County, Mo.
Shipment 256—White ash (*Fraxinus americana*) grown in Pocahontas County, W. Va.
Shipment 257—Biltmore ash (*Fraxinus biltmoreana*) grown in Overton County, Tenn.
Test specimens of shipment 499 were 1.25 by 1.25 inches.
Values of drop, shipment 499 adjusted to 2 by 2 inch sticks.

TABLE 23.—*Commercial white ash.* (*Improvement ratios with and without adjustment to 10 per cent moisture of kiln-dried and air-dried material.*)

[Fiber-saturation point=20 per cent moisture.]

Shipment.	Seasoning.	Static bending.						Impact bending, 50-pound hammer.			Compression parallel to grain.		
		Moisture.	Modulus of rupture.		Modulus of elasticity.		Work to maximum load.		Moisture.	Height of maximum drop.		Moisture.	Maximum crushing strength.	
			I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.	I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.		I. R. as tested.	I. R. adjusted.
		Per ct.							*Per ct.*			*Per ct.*		
75	Air dry	11.4	1.54	1.65	1.22	1.26	1.18	1.21	11.3	1.00	1.00	11.2	1.81	1.96
101	do	10.4	1.78	1.83	1.37	1.39	1.26	1.27	10.8	1.04	1.035	10.5	1.87	1.93
214	do	9.0	1.73	1.65	1.22	1.20	1.04	1.035	9.0	.98	.98	9.5	2.04	1.97
222	do	9.7	1.53	1.51	1.15	1.14	.97	.97	9.3	.97	.97	9.6	1.85	1.77
223	do	9.5	1.61	1.57	1.20	1.19	1.12	1.11	9.3	.82	.83	9.6	1.80	1.76
256	do	7.0	1.92	1.65	1.31	1.23	.98	.985	6.2	.98	.99	6.9	2.50	2.01
257	do	5.6	1.68	1.43	1.32	1.21	1.01	1.08	5.3	1.55	1.35	5.4	2.60	1.92
[1] 499	Kiln run 81	4.4	1.23	1.20	1.18	1.16	.62	.66	4.8	1.17	1.14	4.7	2.02	1.82
	Kiln run 82	7.2	1.30	1.35	1.17	1.20	.84	.82	7.2	.31	.30	7.4	1.80	1.91
	Kiln run 83	6.2	1.56	2.00	1.12	1.20	1.03	1.05	5.9	1.30	1.42	6.8	1.35	1.85
505	Kiln run 90	8.9	1.56	1.49	1.197	1.15	.94	.95	8.8	.84	.86	9.0	1.88	1.78
	Air dry	12.9	1.45	1.69	1.16	1.23	.96	.94	12.8	.79	.72	12.5	1.82	2.22
	Kiln run 96	12.2	1.62	1.85	1.25	1.33	1.18	1.24	11.9	.82	.78	12.0	1.77	2.05
	Air dry	13.0	1.52	1.83	1.19	1.28	1.07	1.10	13.4	.835	.76	12.9	1.66	2.05
	Kiln run 97	12.9	1.46	1.70	1.25	1.37	1.07	1.10	11.9	.89	.87	12.6	1.65	1.97
	Air dry	13.0	1.47	1.74	1.18	1.27	1.00	1.00	13.2	.90	.86	12.9	1.66	2.05
507	Kiln run 92	11.0	1.57	1.65	1.24	1.27	1.01	1.01	11.1	.85	.83	11.0	1.87	2.00
	Air dry	12.7	1.47	1.70	1.19	1.27	.93	.90	12.6	.79	.73	12.8	1.71	2.10
	Kiln run 100	11.3	1.56	1.67	1.28	1.33	.97	.96	11.2	.78	.75	11.0	1.87	2.01
	Air dry	12.6	1.48	1.70	1.21	1.29	.915	.89	12.7	.79	.72	12.8	1.72	2.12

[1] I. R. as tested= $\frac{\text{kiln-dried}}{\text{air-dried}}$ (no green to match).

TABLE 24.—*Efficiencies for kiln runs on white ash.*

Property.	F	Shipment 505.						Shipment 507.			
		Kiln run 90.		Kiln run 96.		Kiln run 97.		Kiln run 92.		Kiln run 100.	
		E	E×F	E	E×F	E	E×F	E	E×F	E	E×F
		Per cent.		*Per cent.*		*Per cent.*		*Per cent.*		*Per cent.*	
Modulus of rupture	2	88.1	176.2	101.1	202.2	97.7	195.4	97.0	194.0	97.7	195.4
Modulus of elasticity	4	93.5	374.0	103.8	415.2	107.9	431.6	100.0	400.0	103.1	412.4
Work	3	101.1	303.3	112.8	338.4	110.0	330.0	112.1	336.3	107.9	323.7
Drop	3	119.2	357.6	102.7	308.1	101.1	303.3	113.6	340.8	104.1	312.3
Compression parallel	2	80.3	160.6	100.0	200.0	96.2	192.4	95.3	190.6	94.8	189.6
Σ(E×F)	....	.....	1,371.7	.....	1,463.9	.....	1,452.7	.....	1,461.7	.....	1,433.4
Σ(E×F)÷ΣF=weighted average E	....	.....	98.0	.....	104.6	.....	103.8	.....	104.4	.....	102.4
ΣE	....	482.2	.....	520.4	.....	512.9	.....	518.0	.....	507.6	.....
ΣE÷5=average E	....	96.4	.....	104.1	.....	102.6	.....	103.6	.....	101.5	.....

F=Weighting factor

E=Efficiency= $\frac{\text{Improvement ratio for property of kiln dry}}{\text{Improvement ratio for same property of corresponding air dry}}$

CONCLUSIONS.

From the above discussion the following conclusions are drawn:

1. Runs 81 and 82, made on partially air-dried material at high temperatures (180° to 210° F.) and with comparatively low humidities, resulted in rather severe damage to the important properties of work to maximum load and drop. (It is notable that neither of these runs produced any *visible* damage.)

2. Run 83 on partially air-dried material, and 90, 96, 97, 92, and 100 on green, at more moderate temperatures (initial 100° to 125° F. and maximum 120° to 160° F.) and somewhat higher humidities, have all produced material practically equal in mechanical properties to air-dried.

3. Results of this latter group of kiln runs furnish no basis for coordination between severity of kiln conditions and effect on mechanical value of the product.

4. From 2 follows the conclusion that Table 1 of Specification 20500–A is a safe schedule for the drying of white ash.

RECOMMENDATION.

It is recommended that in drying white ash for use where the retention of maximum strength is essential, the temperatures of Table 1 of Specification 20500–A should not be exceeded.

PORT ORFORD CEDAR.

Four kiln runs have been made on Port Orford cedar. The runs were numbered 124, 125, 126, and 157.

Kiln run 124 subjected the stock to slightly milder conditions than those specified in Table 1, Specification 20500–A.

Run 125 was made under rather severe high-temperature conditions. From an initial temperature of 165° F. and a relative humidity of 80 per cent, near the fiber-saturation point the temperature reached 175° F. and the relative humidity 40 per cent, ending with a temperature of 152° F. and a relative humidity of 35 per cent.

The temperatures and humidities called for by Table 2 of Specification 20500–A were used as a basis for the conditions of kiln run 126.

For kiln run 157, a practically constant temperature of 120° F. with a relative humidity of 80 per cent was used.

PHYSICAL RESULTS.

The average moisture content of green material in all four runs was 35 per cent, with samples from 124 containing 32 per cent, 125 containing 38.2, 126 containing 35.5, and 157 containing 33 per cent. The moisture contents were reduced to 8, 4, 8.2, and 8 per cent respectively. The time varied from eight days for run 125 to thirty-eight days for run 157, with run 124 taking nineteen days and run 126 twenty-eight days. Runs 124 and 125 showed practically no visible degrade, while runs 126 and 157 showed 3 and 8 per cent, respectively.

MECHANICAL RESULTS.

Comparison of kiln-dried material with previously tested air-dried material shows improvement ratios for the kiln-dried material lower in varying degrees than for air-dried material for all properties except maximum crushing strength in compression parellel to grain. The kiln material approximately equals air-dried in modulus of elasticity in static bending, lagging slightly behind air-dried material in modulus of rupture in static bending, and dropping well behind the air-dried for work to maximum load in static bending and drop in impact bending. There are no appreciable differences in the improvements of the first three kiln runs, all being exceptionally uniform. Run 157, however, is somewhat erratic. It is noticeably higher than the previous runs in improvement in work to maximum load, and noticeably lower in drop in impact bending.

CONCLUSIONS.

The previously tested air-dried material with which the kiln-dried is compared came from one tree only, and from evidence at hand it is concluded that it showed exceptional improvement in air drying. It is therefore probable that the kiln-dried material gave as great improvement as it would have done had it been subjected to a long period of air seasoning. A comparison of various kiln runs shows no significant difference in the improvement in strength values between the different runs, in spite of a considerable range of the temperatures used in drying.

RECOMMENDATIONS.

In view of the fact that positive conclusions can not be reached until tests have been made on air-dried material corresponding to that kiln-dried, and the further fact that any lack of control of kiln conditions is more likely to result in damage when attempting to run by a high-temperature schedule, it is recommended that higher temperatures and lower humidities than those of Table 1, Specification 20500–A, should not be used in drying Port Orford cedar, unless there is urgent need for rapid drying, and then only in case the kiln operation is in charge of an experienced man.

BALD CYPRESS.

One kiln run has been made on bald cypress. In this run 2 and 3 inch material was dried, using the temperatures and humidities of Table 1 of Specification 20500-A. During the last two weeks of the run it was not possible to reduce humidity below 40 per cent, thus causing a departure to that extent from Table 1. It was necessary to steam nine different times at temperatures ranging from 150° to 176° F. for periods of one to five hours, to relieve casehardening. (Total time of steaming 24½ hours.)

PHYSICAL RESULTS.

The average moisture content was reduced from 91.8 to 7.3 per cent in 80 days, with an average visible degrade of 8 per cent due to springing and warping.

The material from butt logs was found to dry much more slowly than that from upper logs.

MECHANICAL RESULTS.

The kiln-dried material gave practically as great an improvement in static bending as previously air-dried material, the former being noticeably greater in "work". The kiln-dried material from lower bolts gave a greater improvement than that from the upper bolts in every case except drop in impact bending. In this property, and also in maximum crushing strength in compression parallel to grain, the air-dried material gave a greater improvement than the kiln-dried material.

CONCLUSIONS.

It is not possible from results in one kiln run to form final conclusions on the proper method of kiln drying this species. From data collected it is concluded that:

1. Upper-log material can be dried much more rapidly than that from butt logs, and the two classes should be dried separately.
2. Cypress requires more than ordinary care in drying in order to prevent checking, honeycombing, warping, and casehardening.
3. Cypress can be kiln dried so as to produce material equal in its mechanical properties to air-dried material, but final judgment on this point can not be reached until matched materia has been air dried and tested.

RECOMMENDATIONS.

1. That butt-log material and material from upper logs be kiln dried separately.
2. That, pending the results of further tests, the temperatures of Specification 20500–A should not be exceeded in drying bald cypress, and that humidity and steaming be regulated to keep casehardening at a minimum.

WESTERN HEMLOCK.

Two kiln runs have been made on 3-inch material of this species. In one run the material was dried by using temperatures and humidities approximately as called for by Table 1, Specification 20500–A (temperatures 120° F. initial, and 145° F. final; humidities 80 per cent initial, and 35 per cent final). This resulted in decreasing the moisture content from an average of 79 per cent to an average of 6.7 per cent in a period of 33 days, with a resultant visible degrade of 3 per cent due to opening up of checks.

The second, which was a high-temperature run (temperatures 160° F. initial to 180° F. final, with humidities 70 per cent initial to 50 per cent final), compares favorably with the first run both in time required for drying and in amount of degrade. The time was 19 days to reduce the moisture content from 98.4 per cent to 8.2 per cent, as compared with 25 days to reduce to 4.8 per cent for the first run. The average visible degrade was less than 1 per cent. The first run had only slight indications of casehardening on resawing, while severe casehardening was indicated in the second run.

MECHANICAL RESULTS.

The two runs are practically equal to each other and to previously-tested air-dried material in improvement of modulus of rupture and work to maximum load in static bending. However, in modulus of elasticity, while the high temperature run equals the air-dried, the Table 1 run falls

considerably lower. Both runs fail to show improvement equal to that shown by previously tested air-dried material in impact drop and compression parallel to grain. Were it not for the known facts concerning the variability of timber—and of improvement ratios as previously brought out in this report—cases of inferiority in improvement to previously air-dried material might be assumed to indicate actual damage resulting from kiln drying. However, the fact that the more severe kiln conditions have produced material practically equal in all and considerably superior in some properties to that resulting from kiln drying under milder conditions is accepted as the better basis of judgment. Groups of material tested after drying in the two kiln runs are closely matched to each other; hence, comparisons between the runs are much more accurate and positive than comparisons with the air-dried material.

CONCLUSIONS.

The conclusion that neither kiln process damaged the material must be regarded as tentative, pending testing of matched air-dried material, but it is believed that conditions scheduled in Table 1 of Specification 20500–A are safe for drying western hemlock. Probably considerably higher temperatures could be used without damage.

RECOMMENDATIONS.

In view of the fact that positive conclusions can not be reached until tests have been made on air-dried material corresponding to that kiln dried, and the further fact that any lack of control of kiln conditions is much more likely to result in damage when attempting to run by a higher temperature schedule, it is recommended that Table 1 of Specification 20500–A be used in drying western hemlock.

WHITE AND NORWAY PINE.

Material of both white and Norway pine was dried in each of two kiln runs. One run was made with temperature varying from 180° to 200° F. and relative humidity varying from 76 to 60 per cent. The second kiln run followed quite closely the schedule of temperatures and relative humidities of Table 1 of Specification 20500–A.

PHYSICAL RESULTS.

The result of the first run was that the white pine was dried from an average moisture content of 99 per cent to an average of 5.3 per cent and the Norway pine from 22.5 to 6 per cent in a period of 16 days. Both species had a visible degrade of about 6 per cent, due mostly to checking. The high temperature caused the pitch and resin to flow to the surface and harden.

In the second run the white pine was dried from an average moisture content of 99 per cent to an average of 10 per cent and the Norway pine from 35.5 per cent to 8.6 per cent in a period of 67 days. Both species had a visible degrade of 6 per cent, due to checking, twisting, and warping.

MECHANICAL RESULTS.

The results from the mechanical tests on small clear specimens indicate that the two runs produced approximately as good improvement in nearly all values as resulted from previous air drying and that, in spite of the great difference in temperature, the two runs produced about equally good results. The high-temperature run gave considerably better improvement in modulus of rupture and maximum crushing strength of Norway pine, and slightly better in modulus of elasticity of both species, while in other values the low temperature run gave slightly, but not significantly, better improvement.

CONCLUSIONS.

It is concluded that there is no damaging effect to be expected from temperatures as high as were used in this instance. This conclusion, however, must be regarded as tentative until confirmed or disproved by tests on matched material which is now air drying.

RECOMMENDATIONS.

Table 1 of Specification 20500–A is recommended for use in drying these species until additional data can be obtained on the effect of various temperatures and relative humidities on the strength.

WHITE FIR.

Two kiln runs have been made on white fir, in stock of 3-inch thickness and various widths. The temperature in one run ranged from 160° F. initial to 180° F. final. The other run followed quite closely the schedule of Table 1 of Specification 20500–A, as shown in Table 25.

TABLE 25.—*Kiln conditions used in runs 157 and 158, compared with Table 1 of Specification 20500–A.*

Stage of drying.[1]	Average drying conditions.					
	Temperatures.			Humidities.		
	Kiln run 157.	Kiln run 158.	Table 1.	Kiln run 157.	Kiln run 158.	Table 1.
	Degrees F.	*Degrees F.*	*Degrees F.*	*Per cent.*	*Per cent.*	*Per cent.*
At the beginning	120	163	120	80	70–80	80
After fiber-saturation point is passed (25 per cent moisture)	120	165	125	80	75	70
At 20 per cent moisture	120	170	128	80	75	60
At 15 per cent moisture	125	177	138	70	71	44
At 12 per cent moisture	125	179	142	60	71	38
At 8 per cent moisture	140	181	145	37	68	33
Final	145	180	145	33	50	33

[1] As determined from moisture contents of samples.

Kiln run 157.—This run was made in a kiln which had been equipped with fans to produce circulation.

The material was steamed 18 hours at 136° F. before the kiln conditions given in Table 25 were established. Casehardening stresses which developed during the run made four additional steamings necessary, at temperatures of 135° to 160° F., for periods of one to two hours. (Total time, six hours.)

Drying from an average moisture content of 100 to 8.2 per cent was accomplished in 57 days, with an average visible degrade of about 8 per cent. This degrade was the result of twisting, warping, and surface checking.

Kiln run 158.—This run was started without preliminary steaming, but it was necessary to steam six times (total time 19 hours) during the run to relieve casehardening. The steaming periods ranged from one and one-half to six hours, at temperatures ranging from 170° to 182° F.

The material was dried from an average moisture content of 149 to 7.7 per cent in 12 days; but in order to relieve casehardening it was necessary to continue the run for 9 days, during which the moisture content of the samples was reduced to 5.1 per cent. The moisture content of the green material ranged from 69 to 208 per cent.

The material was in good condition on entering the kiln, although several pieces showed end and heart checks, shakes, and springing. After being dried the material came out with an average degrade from warping, springing, twisting, and surface checking of approximately 6 per cent.

DISCUSSION AND CONCLUSIONS.

The material was compared with various air-dried firs (silver, grand, and noble) as well as white fir. In every case, except maximum drop in impact bending, kiln run 157 is superior to the average of the air-dried firs. Kiln run 158 is somewhat lower than this average in maximum drop in impact bending and in maximum crushing strength in compression parallel to grain.

Both runs produced material which was better in improvement of strength properties than material from the one available tree of air-dried *white* fir, except in compression parallel to the grain. In this property the high-temperature run (158) was inferior to the air-dried material.

It appears that no significant damage occurred to the strength properties from either kiln treatment, and it is probable that the Table 1 run (157) produced at least as good results as would have resulted from air drying.

RECOMMENDATIONS.

1. Pending the completion of tests on air-dried material matching that kiln dried, it is recommended that Table 1 of Specification 20500–A be used in drying white fir for use where maximum strength is essential.

2. If faster drying than can be produced by following the above recommendation is necessary, the temperatures as used in run 158 appear to be fairly safe, providing the humidity is regulated to prevent severe casehardening.

3. Because of the large variation in moisture content of different boards of this species, it is recommended that this material be divided into two or more groups according to the weight of the pieces, which is an indication of the moisture content, and that either the groups be kiln dried separately or the heavier material be placed in the most rapid drying part of the kiln.

AFRICAN AND CENTRAL AMERICAN MAHOGANIES.

Mechanical tests have been made on small, clear specimens of material from several experimental kiln runs on African and Central American mahoganies. Runs 106, 107, 108, and 109 included both species. Central American mahogany was dried in runs 161 and 162, and African mahogany in runs 164 and 165.

The ranges in temperatures and humidities for all eight runs are given in Table 26, which also lists, for the purpose of comparison, the temperatures and humidities of Tables 1 and 2 of Specification 20500–A.

TABLE 26.—*Kiln conditions used in runs 106, 107, 108, 109, 161, 162, 164, and 165, compared with Tables 1 and 2 of Specification 20500–A.*

Stage of drying.	Average drying conditions—temperatures.									
	Kiln run 106.	Kiln run 107.	Kiln run 108.	Kiln run 109.	Kiln run 161.	Kiln run 162.	Kiln run 164.	Kiln run 165.	Table 1.[1]	Table 2.[1]
	Degrees F.	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*	*Degrees F.*
The beginning	105	180	90	120	105	120	105	115	120	105
After fiber saturation point is passed (25 per cent moisture)	108	180	95	120	106	128	108	104	125	110
At 20 per cent moisture	110	180	106	120	106	130	110	107	128	117
At 15 per cent moisture	115	180	118	130	116	128	118	118	138	129
At 12 per cent moisture	116	180	118	120	128	150	131	120	142	135
At 8 per cent moisture	.....	.....	.....	.....	135	154	130	120	145	135
Final	118	160	120	138	135	147	90	129	145	135

Stage of drying.	Average drying conditions—humidities.									
	Kiln run 106.	Kiln run 107.	Kiln run 108.	Kiln run 109.	Kiln run 161.	Kiln run 162.	Kiln run 164.	Kiln run 165.	Table 1.[1]	Table 2.[1]
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
The beginning	85	85	86	80	94–85	80–88	97	82	80	85
After fiber saturation point is passed (25 per cent moisture)	75	85	75	70	80	78	74	80	70	73
At 20 per cent moisture	72	90	65	72	76	76	74	74	60	62
At 15 per cent moisture	68	85	50	.....	57	72	65	60	44	46
At 12 per cent moisture	65	85	42	.....	50	61	42	50	38	42
At 8 per cent moisture	.....	.....	.....	.....	46	64	43	50	33	40
Final	60	80	42	54	46	64	60	55	33	40

[1] These are maximum allowable temperatures and minimum allowable humidities.

The length of time required for drying, the amount of degrade, and the original and final average moisture content for each run are all given in Table 27.

TABLE 27.—*Physical results of various kiln runs of African and Central American mahoganies.*

Species	African mahogany.						Central American mahogany.					
Kiln run	106	107	108	109	161	162	106	107	108	109	164	165
Days in kiln	42	14	21	20	21	24	42	14	21	20	13	25
Average per cent moisture content, initial	66.5	56.6	70.0	69.6	60.0	60.3	66.5	56.5	70.0	69.6	41.0	48.7
Average per cent moisture content, final	9.9	10.0	12.0	8.4	8.9	8.6	9.9	10.0	12.0	8.4	7.7	8.4
Per cent visible degrade	None.	2.0	1.0	1.0	2.4	3.0	None.	2.0	1.0	1.0	2½	4½

The material for all runs was approximately 1 inch in thickness.

The material for all runs except 108 was steamed before drying was commenced, and all runs except 106 were again steamed from one to four times to relieve casehardening. The steaming for run 162, however, was to relieve only very slight casehardening.

MECHANICAL RESULTS.

African mahogany.—A decided gain in improvement was made by all kiln runs over the previously tested air-dried material in modulus of rupture and maximum drop. Work to maximum load, modulus of elasticity, and maximum crushing strength may all be considered equal to the average of the air-dried in improvement.

No apparent damage is shown in any kiln run, and the material is considered to have made at least as good improvement as would have resulted from air drying.

Central American mahogany.—Material from all the kiln runs shows very good improvement in strength properties over the corresponding green material. Improvement ratios are in nearly every case as high as resulted from the air drying of material previously tested.

There appears to be but very little difference in the improvement for the various strength properties produced by the different processes of drying.

DISCUSSION AND CONCLUSIONS.

The satisfactory results from these kiln runs indicate that the temperatures of both Tables 1 and 2, Specification 20500–A, are safe, as four of the runs were made with temperatures approximately those called for by Table 1 or 2, and one run subjected the stock to severer temperatures.

The consistent though slight inferiority of the high-temperature run (107) to run 106, which was made on material from the same trees, indicates a possible relation between strength and temperature used in drying.

Run 162, the material in which was Central American mahogany, was made with temperatures closely approximating those of Table 1, but the relative humidities were not permitted to drop below 60 per cent. This run produced material which was in excellent condition for propeller stock and which was slightly better in improvement of strength properties than material from the same shipment dried in run 161. While no run was made on African mahogany using conditions similar to run 162, it is believed, since the two woods are seemingly closely related in physical properties, that such a run would produce practically the same results. Special tests taken on this run showed even cross-sectional drying and very slight casehardening. These results indicate that the condition under which the material in run 162 was dried is very satisfactory for drying propeller stock.

RECOMMENDATIONS.

It is recommended that in drying Central American and African mahoganies, the temperatures of Table 1 of Specification 20500–A be used, but that the relative humidity be not allowed to drop below 60 per cent at any time during the run.

BLACK WALNUT.

In order to develop a process of kiln drying black walnut satisfactorily, two kiln runs were made, one in accordance with Table 1 and the other in accordance with Table 2 of Specification 20500–A.

The Table 1 run consisted of 1-inch and the Table 2 of both 1 and 2 inch stock.

The Table 2 run was controlled by both 1 and 2 inch samples, which delayed the drying process slightly as the 2-inch material dried very slowly. The 2-inch samples were discarded from calculations during the last stages of the run and conditions better adapted to 1-inch stock were secured. The material was steamed at 120° F. for six hours at the beginning and for one hour at 150° F. at the end of the run, the latter to relieve casehardening.

The 1-inch material dried from an average of 72 to an average of 8 per cent in a period of 38 days, but 2-inch material in the same period reduced only to 18 per cent from 54 per cent. The material entered the kiln with end and heart checks, heart rot, and springing, and came out with an average degrade of about 7 per cent caused by springing, checking, and warping.

The condition of the second run during the final stages was slightly milder than required by Table 1 of Specification 20500-A. The material was frozen when loaded into the kiln and it was necessary to thaw it out, by steaming, before drying could begin. Toward the end of the run it was necessary to steam the material one hour at 150° F. to relieve casehardening.

At the beginning of the run the stock contained an average moisture content of 78.6 per cent, which was reduced to 7.7 per cent in 31 days. It left the kiln in good condition, showing a visible degrade of about 2½ per cent caused by end checking.

CONCLUSIONS.

The improvement ratios show that, with exception of drop in impact bending, both kiln runs produced greater improvement in strength properties than resulted in the case of the previously air-dried material, and in all probability as good results as would have been obtained by air drying the same material. As both runs follow closely Tables 1 and 2 of the specification, it follows that either of these tables can be expected to give satisfactory results when used for drying 1-inch black walnut. The strength data give no basis for a choice between the two kiln runs.

RECOMMENDATIONS.

The work so far done gives, of course, no basis for judging the effect of conditions more severe than Table 1. Until the effect of more severe conditions can be ascertained, it is recommended that Table 1 of Specification 20500-A be used for drying black walnut.

SUGAR MAPLE.

Seven experimental kiln runs in the drying of sugar maple have been made, but only the first three, 132, 133, and 134, have reached a stage where discussion and analysis are possible and figures are available.

The first run (132) was on 1-inch material only; the last two runs (133 and 134) were on both 1-inch and 2-inch material. Run 132 was made to determine the effect of a practically constant temperature of 170° F. and the same relative humidities as called for by Table 2 of Specification 20500-A; run 133 was in accordance with Table 1, and run 134 was in accordance with Table 2 of this specification. Runs 133 and 134 were both steamed near the end of the run to relieve casehardening. No steaming was necessary on run 132.

The high-temperature run (132) was made in the least time, requiring 12 days, but had the smallest difference between initial and final moisture contents, the initial moisture content being 48 and the final 8 per cent. This run had the largest average degrade—about 15 per cent. The degrade was due chiefly to warping, with some springing and twisting. Slight casehardening was evident on resawing.

The Table 1 run (133) required 23 days, practically twice the time of the previous run, but reduced the average moisture content from 56 to 5.8 per cent, with an average degrade of 11 per cent due to cupping, warping, and springing, the greater portion being due to cupping. Very little casehardening developed on resawing.

Kiln run 134 required 29 days to reduce the average moisture content from 56 to 7.5 per cent, but had the smallest degrade of any run—about 8 per cent, due to cupping and warping. The material showed very slight reverse casehardening on being resawed.

RESULTS.

There is no marked or consistent difference in the mechanical results of the three runs. The kiln-dried material showed improvement over matched green material equal or superior to that previously obtained by air drying.

CONCLUSIONS.

Absolutely definite conclusions can not be reached until tests on corresponding air-dried material have been made; but the data warrant the conclusions:

1. That kiln drying can be carried on without injury of material, and probably with better results than can be obtained by air drying.
2. That there are no consistent differences in the effects of the three runs. This indicates that a considerable range of temperature can be employed with little, if any, difference in the effect on the mechanical properties.

RECOMMENDATIONS.

Until the above conclusion (No. 2) has been checked by tests on corresponding air-dried material, and because of the greater danger of damage through accidental departure from schedules when operating at higher temperatures, it is recommended that maple be dried by schedule of Table 1 of Specification 20500–A.

YELLOW BIRCH.

Five kiln runs have been made on yellow birch, as follows:

Run 84 was on 2½-inch plank, with temperatures 130° F. initial to 180° F. final, initial and final humidities of about 77 and 13 per cent, respectively. The average moisture content was reduced from 60 to 4 per cent in about 31 days. There was evidence of casehardening in some parts of the pile at the end of the run.

Run 168 was on 1-inch stock. Temperatures were approximately those of Table 1. Initial and final humidities were about 80 and 35 per cent, respectively. The material was steamed six times, at temperatures varying from 150° to 165° F. and periods of one-fourth to one hour, for the relief of casehardening, which persistently developed. There was slight casehardening at the end of the run. Uneven sawing, which prevented proper piling and weighting of the stock, was chiefly responsible for the degrade of about 10 per cent. Moisture content was reduced from 64 to 7.6 per cent in 16 days.

Run 169 was on 1-inch stock. Kiln conditions were approximately those of Table 1, Specification 20500–A. Steaming three times, at 160°, 170°, and 160° F. for three hours, two hours, and two hours, respectively, near the end of the run, left part of the stock severely casehardened and part in a condition of severely reversed casehardening. Degrade was about the same as in run 168 and due to the same causes. Moisture content was reduced from 58 to 8 per cent in 17 days.

Run 170 was on 1-inch stock, with kiln conditions approximately as prescribed by Table 2 of Specification 20500–A. Five steamings were made at about 20° F. above the scheduled drying temperatures. The stock was practically free from casehardening at the close of the run. Degrade of about 7.5 per cent resulted from the same causes as in run 168. Moisture content was reduced from about 65 to 8.2 per cent in 31 days.

Run 203 was made on 1-inch partially air-dried stock. Kiln conditions were approximately those of Table 1. Steaming for one hour at 160° F. on the eighth day and for two hours at 170° F. on the tenth day successfully relieved the casehardening which had developed. The moisture content was reduced from 18.5 to about 7 per cent in 10 days. There was about 5 per cent degrade.

MECHANICAL RESULTS.

Comparisons by means of improvement ratios indicate that runs 168, 169, and 170 produced practically equal improvement, and that this improvement is equal to the average of two trees previously air dried, being less than one and greater than the other. Improvement in run 84 is less than the minimum for the previously air-dried material. Comparisons of run 203 with the others are difficult to make because of the partially air-dried condition of the stock before it was placed in the kiln.

CONCLUSION.

The kiln conditions of Tables 1 and 2 produced results in the drying of yellow birch which are equal to those to be expected from air drying.

It seems probable that the one run at temperatures of 130° to 180° F. has failed to produce as good results as would have been obtained from air drying.

RECOMMENDATIONS.

Both Table 1 and Table 2 of Specification 20500–A are recommended as suitable for the drying of yellow birch.

OAK.

Seven kiln runs were made on oaks, including red and white oak species from the South and white oak (presumably true white (*Quercus alba*)) from northern Indiana. The testing work, inclusive of tests on air-dried material, has been entirely completed. The data, however, are very erratic and it is difficult to arrive at consistent conclusions.

One run (A), at temperatures varying from 150° to 165° F. and relative humidities from 85 to 60 per cent, produced very good results from the strength standpoint on southern red and white oak species, with the exception of Spanish oak. The charge was steamed for one hour and two hours at temperatures of 179° and 170° F., respectively, to relieve casehardening stresses. However, this run resulted in a degrade of 60 per cent as determined from inspection before and after kiln drying. The causes of degrade included severe casehardening, warping, cupping, honeycombing, and collapse.

Two runs (B and C) on northern white oak gave entirely satisfactory results from the strength standpoint. Run B was with temperatures approximately as prescribed in Table 2 of Specification 20500–A and relative humidities ranging between 90 and 70 per cent. This run was steamed at 135° F. for one hour to relieve casehardening stresses. Run C was at temperatures of 120° F. initial and 140° F. final, with relative humidities about 90 initial and 50 final. It was necessary to steam this material three times, at temperatures from 160° to 164° F., for a total of two and one-half hours, to relieve casehardening stresses at the end of the run. Both gave results fully equal to air dry, with the lower temperature run (B) slightly the better. Material in both cases came from the kiln in excellent condition, there being less than 1 per cent degrade in run B and less than 1½ per cent in run C.

In another run (D), with temperatures 90° F. initial to about 125° F. final and humidities ranging from saturation down to 40 per cent, northern white oak came from the kiln with about 1 per cent degrade, resulting from springing and warping. At the close of the run the charge was steamed seven hours at 155° F. to relieve the casehardening stresses. Strength tests indicated that this material was slightly deficient in strength properties as compared to matched air-dried material.

Still another run (E), with initial temperature of about 100° F. to final 130° F. and humidities ranging from saturation to about 45 per cent, resulted in about 7½ per cent degrade. The material was steamed twice at 185° and 170° F. to kill mold and mildew. A final steaming at 180° F. was to relieve casehardening stresses. This run, however, included southern red oak and both northern and southern white oaks, and while the different species were not separately graded, it was observed that the degrade was more serious in the red than in the white oak. The northern white oak from this run was also slightly deficient in strength properties as compared to matched air-dried stock.

Southern white oak was included in runs A and E, as above described. Run A produced quite satisfactory results from the strength standpoint, while run E resulted in a considerable loss of strength as compared to air-dried material.

Two additional runs, F and G, included southern white oak. Run F was made with temperatures of 105° F. initial and about 135° F. final and relative humidities 85 initial to about 40 per cent final—approximately the condition of Table 2. Run G was with temperatures of 120° F. initial to about 140° F. final and with humidities as in F. These runs included also southern red

oak species. Run F was steamed three times for periods of one hour each, at 155° F., to relieve casehardening stresses. The degrade in run F was 12 per cent, from warping, springing, and cupping; while G resulted in 50 per cent degrade from springing, warping, cupping, checking, twisting, collapse, honeycombing, and casehardening. Run G was steamed on three occasions for periods of one-half hour, at temperatures of 150° to 170° F., to relieve casehardening stresses. Run F gave quite satisfactory results from the strength standpoint, while in G the results were unsatisfactory, there being a loss of 25 to 30 per cent in modulus of rupture, work to maximum load, and height of drop in impact. Exclusive of Spanish oak, the results from the strength standpoint were as follows:

Southern red oaks, including Spanish oak, were dried in runs A, E, F, and G. Run F produced approximately as good material as air dry, run G material considerably inferior to air dry, and run E, as indicated by maximum drop in impact and maximum crushing strength in compression parallel (there being no static bending tests), material very much inferior to matched air-dried stock.

None of these runs (A, E, F, and G) gave satisfactory results from the strength standpoint on Spanish oak. Runs F and G resulted in losses in all strength properties, with F possibly slightly superior to G. Run A gave results somewhat superior to either F or G, while the results in E were inferior to either F or G.

From the results as presented above it is concluded: (1) That under the same kiln conditions northern white oak can be expected to dry with smaller losses, both from the strength standpoint and the standpoint of degrade in appearance, than southern oaks, either red or white; (2) that of the southern oaks the red oak species require more care than the white oak species; (3) that Spanish oak is considerably more liable to damage of strength properities in kiln drying than the other red oak species from the southern region; (4) that, in general, the northern oaks are more easily kiln dried than the southern.

It is evident from experience in these runs, and the conclusion is borne out by experience in drying oak on a commercial scale, that the maintenance of suitable kiln conditions requires more care in the case of oaks than in other species or groups of species. Oak has been found in all experimentation with it, as well as in its utilization, to be more variable than other species. To attempt to specify beforehand exactly what kiln condition should be used seems unwise. The results of these kiln-drying and strength tests indicate that the temperatures of Table 1 of Specification 20500–A are probably the maximum which are safe for northern white oak, and likewise that the temperatures of Table 2 should not be exceeded in drying southern oak, either red or white. In drying any of the oaks very careful attention must be given to the condition of the stock in all parts of the kiln. Temperatures and humidities must be regulated not only by the moisture content of the stock but also by its condition with respect to checking, casehardening, the existence of a difference in moisture content between the outside and the inside of the piece, and the existence of stressed conditions.

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REPORT No. 69

A STUDY OF AIRPLANE RANGES AND USEFUL LOADS

By J. G. COFFIN
Director of Research, Curtiss Engineering Corporation

Part I.—NUMERICAL ANALYSIS
Part II.—THEORETICAL ANALYSIS
Part III.—EFFECT OF WIND ON RANGE

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INTRODUCTION.

In airplane performance estimates the fuel load is given usually in terms of a quantity sufficient for a certain number of hours of motor consumption at full throttle. In a weight-carrying machine more useful load can, of course, be carried as the fuel load required to attain the objective is diminished.

It becomes, therefore, of practical interest to examine the relations between these loads in greater detail than usual.

A machine can fly high or low, at maximum speed or at most economical speed, or at most economical power consumption. It is not at all evident a priori which of these or what combination of them is best under given conditions. The following study was primarily made to determine the conditions necessary to attain a given objective with the maximum bombing load and return.

It is, of course, evident that the calculations and theory as applied to bombing purposes will apply equally well for commercial load carrying purposes. The results are also directly applicable to the interesting questions of long distance flights, across the oceans or for purposes of exploration.

The investigation was made by two independent methods, one involving the usual performance estimate methods, the other based upon theoretical considerations.

As a specific example the data on an 800-horsepower, 15,000-pound bombing machine was used, but the method is applicable with slight variations to any machine.

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REPORT NO. 69.

PART I.

NUMERICAL ANALYSIS.

By J. G. COFFIN.

The essential data for the specific machine used in the calculations are given in Table I. The total wing and parasite resistances were computed for assumed total weights of 15,000, 13,000, 11,000, 9,000, and 7,000 pounds respectively The total resistance and required horsepower curves were then plotted against speed in the usual manner. See Table I and Fig. 1.

TABLE I.—*Summary of total resistances for a machine with a variable load. Area of wing=1,875 square feet.*

Weight and wing loading.	Speed in M. P. H.	Monoplane $K_y \times 10^4$.	Biplane K_y= .85 mono K_y $\times 10^4$.	Monoplane K_y/K_x.	Biplane K_y/K_x= .85 mono K_y/K_x.	Wing resistance =W/Bip. (L/D).	Parasite resistance $\times 1.10$.	Total resistance wing+ parasite.	Required horsepower.
						Pounds.	*Pounds.*	*Pounds.*	
15,000 pounds or 8 pounds per square foot	70.0	19.2	16.3	16.2	13.8	1,090	609	1,699	318
	80.0	14.9	12.5	21.2	18.0	834	735	1,569	334
	90.0	11.6	9.9	21.7	18.4	814	937	1,751	421
	100.0	9.40	8.0	19.6	16.7	899	1,151	2,050	547
	110.0	7.82	6.6	16.8	14.3	1,050	1,400	2,450	719
13,000 pounds or 6.92 pounds per square foot	60.0	22.6	19.2	9.3	7.9	1,613	475	2,118	339
	70.0	16.6	14.1	19.8	16.8	773	609	1,382	258
	80.0	12.7	10.8	21.8	18.5	702	735	1,437	306
	90.0	10.0	8.55	20.5	17.4	718	937	1,686	404
	100.0	8.15	6.91	17.3	14.7	884	1,151	2,035	543
	110.0	6.72	5.71	15.0	12.7	1,022	1,400	2,422	710
11,000 pounds or 5.86 pounds per square foot	60.0	19.2	16.3	16.2	13.8	801	475	1,276	204
	70.0	14.1	12.0	21.5	18.3	602	609	1,211	226
	80.0	10.75	9.15	21.3	18.1	608	735	1,343	286
	90.0	8.48	7.23	18.2	15.5	712	937	1,649	396
	100.0	6.90	5.86	15.2	12.9	854	1,151	2,006	535
	110.0	5.70	4.84	13.0	11.1	996	1,400	2,396	702
9,000 pounds or 4.80 pounds per square foot	50.0	22.6	19.2	9.2	7.8	1,152	365	1,517	202
	60.0	15.7	13.3	20.6	17.5	515	475	990	158
	70.0	11.5	9.79	21.6	18.4	491	609	1,100	206
	80.0	8.82	7.50	18.6	15.8	570	735	1,305	278
	90.0	6.97	5.92	15.4	13.1	686	937	1,623	390
	100.0	5.66	4.80	13.0	11.1	815	1,151	1,966	524
	110.0	4.68	3.97	11.2	9.5	946	1,400	2,346	689
7,000 pounds or 3.74 pounds per square foot	42.7	24.0	20.4	6.6	5.6	1,250	270	1,520	173
	50.0	17.6	14.9	18.8	16.0	439	365	804	107
	60.0	12.3	10.4	21.8	18.5	378	475	853	136
	70.0	9.02	7.65	19.2	16.3	429	609	1,038	194
	80.0	6.85	5.84	15.1	12.8	547	735	1,082	274
	90.0	5.44	4.62	12.5	10.6	660	937	1,597	383
	100.0	4.41	3.74	10.6	9.0	777	1,151	1,928	514
	110.0	3.64	3.09	8.4	7.1	981	1,400	2,381	698

CONDITIONS FOR MAXIMUM RANGE.

It is evident that the *work* required to fly a given distance, being the product of the total resistance, or required propeller thrust, by the distance, is least when the thrust is kept at its minimum values. The points of minimum drag were, therefore, located on the resistance curves. These points determined the most economical speeds and the corresponding required powers. The powers thus determined are seen not to be minimum powers. The minimum powers are but slightly less than those corresponding to minimum resistance and occur at speeds slightly less than minimum resistance speeds. The minimum power is that for which the fuel consumption is least for a given *time* and as it turns out, is not the most economical power for flying the greatest distance. The speed corresponding to minimum power is the speed at which a machine should fly in order to remain aloft the greatest possible time.

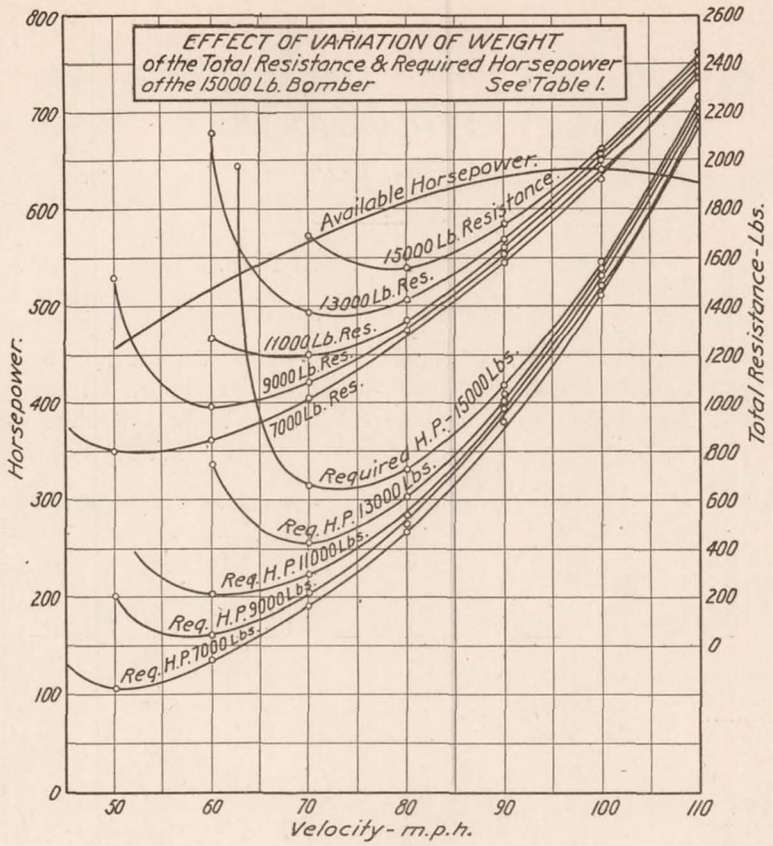


Fig. 1.

In figure 2 the weight of the machine is plotted against minimum resistance. The curves in figures 1 and 2 show that—

1. The maximum range speeds decrease as the load decreases. The plane must fly slower and slower as the load diminishes.

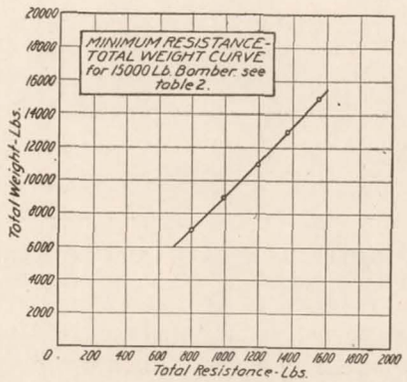


Fig. 2.

2. The maximum range powers decrease as the load decreases.

3. These powers are not minimum powers but are slightly greater and correspond to greater speeds than least power speeds.

4. The total air resistances decrease almost in exact proportion to the weight of the plane.

FUEL CONSUMPTION.

The fuel consumption at maximum brake horsepower output is taken as 0.6 pound per horsepower hour, and for any reasonable throttled condition this number is increased to 0.7.

The available horsepower curve was obtained in the usual manner by assuming proper propeller efficiencies at slow and high speeds and multiplying these into the available brake horsepower. The fuel consumption per horsepower delivered by the propeller can therefore be computed by dividing the fuel consumption per brake horsepower of the motor by the propeller efficiency at that speed, or what is the same thing, multiplying 0.6 by 800 and dividing by the available horsepower at that speed. As mentioned above, these results are multiplied by $\frac{0.7}{0.6}$ in order to compensate for a slight loss of efficiency under throttled conditions. This procedure corresponds to experimental tests and if anything probably overestimates the fuel consumption.

With these data Table 2 and figure 3 were made. The fuel consumption is seen to be proportional to the weight.

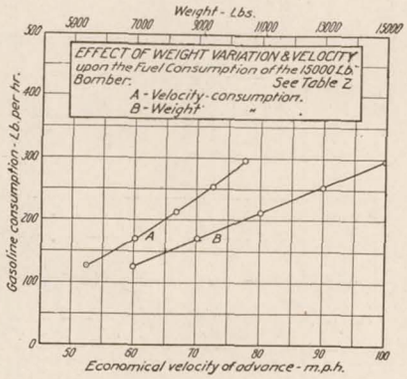


Fig. 3.

TABLE 2.—*Gas consumption in pounds per hour at the economical speed.*

Weight of machine.	Minimum total resistance.	L/D. or weight/tot. res.	Corresponding speed in miles per hour.	Corresponding horsepower.		Gasoline consumption, $\frac{0.7 \times 800}{\text{avail. H.P.}}$ in pounds/per horsepower.	Total gasoline consumption per hour.
				Required.	Available.		
Pounds.	*Pounds.*						*Pounds.*
15,000	1,560	9.62	77.5	320	603	0.927	296
13,000	1,372	9.47	72.5	265	583	.960	254
11,000	1,195	9.22	66.7	212	555	1.009	214
9,000	992	9.08	59.6	159	517	1.082	172
7,000	795	8.82	52.5	107	472	1.187	127

TABLE 2A.—*Gas consumption in pounds per hour at the maximum speed.*

Weight of machine.	Minimum total resistance.	L/D. or weight/tot. res.	Corresponding speed in miles per hour.	Corresponding horsepower.		Gasoline consumption, $\frac{0.6 \times 800}{\text{avail. H.P.}}$ in pounds/per horsepower.	Total gasoline consumption per hour.
				Required.	Available.		
Pounds.	*Pounds.*						*Pounds.*
15,000	2,265	6.63	105.4	636.0	636.0	0.755	480
13,000	2,260	5.75	105.9	635.5	635.5	.755	480
11,000	2,245	4.91	106.3	635.0	635.0	.756	480
9,000	2,225	4.05	106.8	634.9	634.9	.756	480
7,000	2,225	3.15	106.8	634.8	634.9	.756	480

Figure 4 shows a curve giving the relation between the weight at any time and the corresponding distance flown. Starting with a full fuel load of 7,870 pounds, giving a total weight of 15,000 pounds, the machine was assumed to travel for a given time interval (two hours) at the weight, speed, gas consumption, and thrust corresponding to that weight. During the next two hours it was assumed to fly at new values corresponding to the new weight which is equal to the old weight less the fuel consumed in the preceding time interval, and so on.

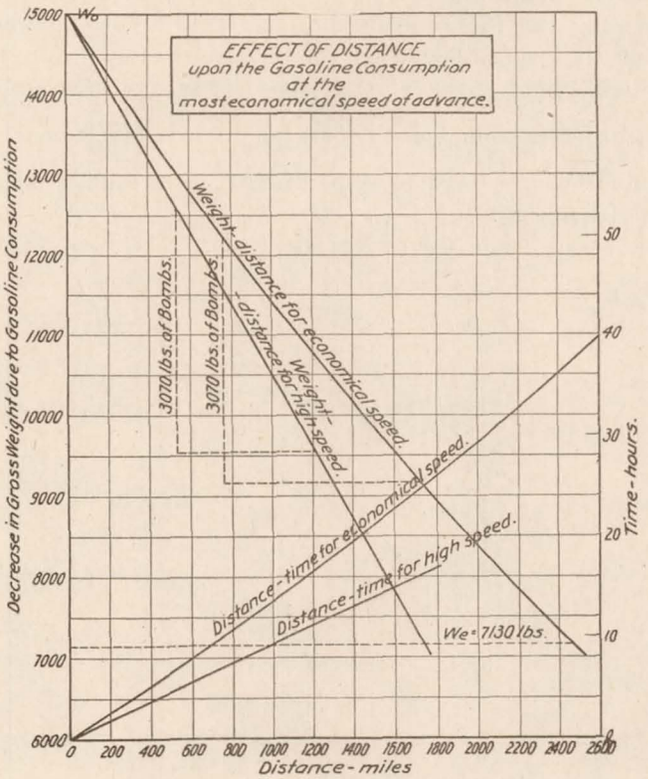


Fig. 4.

TABLE 2B.—*Ratios of L/D and angles of incidence for maximum range.*

MAXIMUM RANGE SPEEDS.

Loading pds./sq. ft.	Biplane L/D.	Velocity, miles per hour.	Biplane, $Ky \times 10^4$.	Monoplane, $Ky \times 10^4$.	Angle of incidence degrees.
8.00	15.55	77.5	13.3	15.65	5.3
6.92	15.63	72.5	13.2	15.55	5.2
5.86	15.63	66.7	13.15	15.50	5.2
4.80	15.38	59.6	13.5	15.90	5.45
3.74	15.30	52.5	13.55	15.95	5.5

HIGH SPEED.

Leading pds./sq. ft.	Biplane L/D.	Velocity, miles per hour.	Biplane, $Ky \times 10^4$.	Monoplane, $Ky \times 10^4$.	Angle of incidence degrees.
8.00	14.45	105.4	7.15	8.41	1.75
6.92	13.17	105.9	6.18	7.27	1.25
5.86	11.65	106.3	5.17	6.07	0.7
4.80	10.03	106.8	4.21	4.95	.2
3.74	3.06	106.8	3.28	3.86	−.35

TABLE 3.—*Time-weight variation computation for speeds*

MAXIMUM RANGE.

Initial weight of machine in pounds.	Thrust in pounds.	Velocity in miles per hour.	Gasoline consumed, pounds per hour.	Distance, miles.		Gasoline consumed in interval. Pounds.	Time in hours.
				S=Vt.	Total.		
15,000	1,560	77.5	297	155.0	155	594	2
14,406	1,500	76.3	286	152.6	307.6	572	4
13,834	1,450	74.9	273	149.8	457.4	546	6
13,288	1,403	73.3	261	146.6	604.0	522	8
12,766	1,355	71.3	250	142.6	746.6	500	10
12,266	1,305	70.5	240	141.0	887.6	480	12
11,786	1,265	69.0	230	138.0	1,025.6	460	14
11,326	1,225	67.5	220	135.0	1,160.6	440	16
10,886	1,185	66.2	210	132.4	1,293.0	420	18
10,466	1,145	64.7	201	129.4	1,422.4	402	20
10,064	1,110	63.5	193	127.0	1,549.4	386	22
9,678	1,065	62.2	184	124.4	1,673.8	368	24
9,310	1,030	61.0	177	122.0	1,795.8	354	26
8,956	995	59.7	169	119.4	1,915.2	338	28
8,618	965	58.6	162	117.2	2,032.4	324	30
8,294	930	57.4	155	114.8	2,147.2	310	32
7,984	900	56.3	148	112.6	2,259.8	296	34
7,688	872	55.1	142	110.2	2,370.0	284	36
7,404	840	54.1	136	108.2	2,478.2	272	38
7,132	815	53.3	132	106.6	2,584.8	264	40

The maximum possible range is seen to be 2,480 miles under these conditions.

DETERMINATION OF THE MAXIMUM LOAD FOR A GIVEN OBJECTIVE.

Evidently in case a return trip is to be made without refueling the greatest distance for an objective is equal to or less than half this greatest range. It is easy to determine the greatest possible useful load by means of the weight-distance curve, figure 5, in the following way:

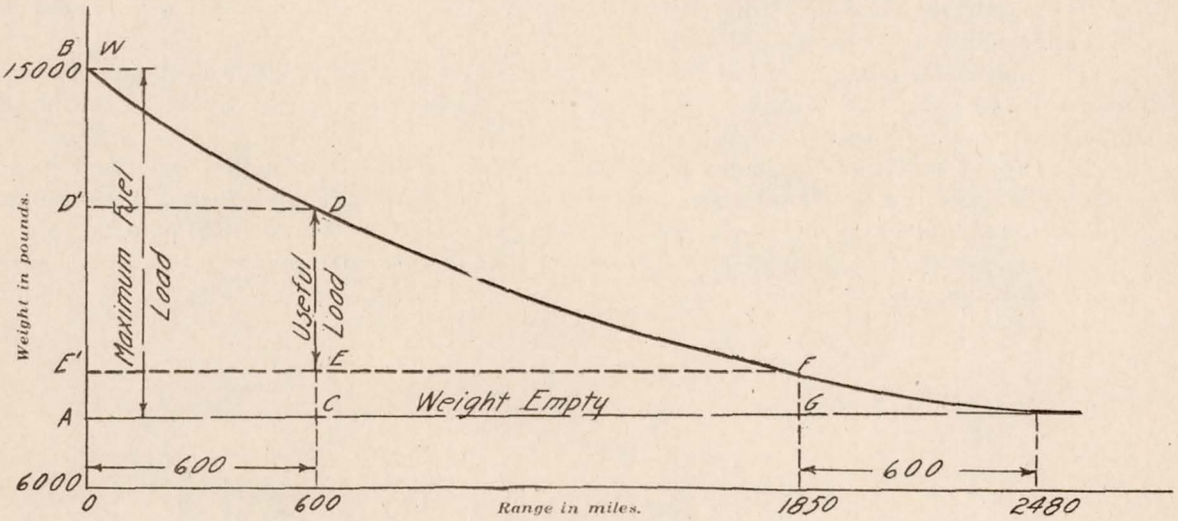


Fig. 5.

Suppose the objective is 600 miles distant. It requires AB–CD pounds of fuel to get there and GF pounds to get back after the load is deposited. Since the maximum load is AB pounds there will be left DE or D′E′ pounds for useful load. Calling the maximum range S, project the points on the curve for $s=600$, point D, and $s=S-600$, point F, on the weight axis, the weight included between these two points is the maximum load for that objective. This procedure is quite general. The load decreases to zero as the objective distance increases to half the maximum range and increases to the maximum load as the objective distance decreases to zero.

A curve (fig. 6) was determined by this method for this machine which gives directly the maximum useful load for any objective. This curve turns out to be practically a straight line. A proof that it should be very approximately straight is given in Part II.

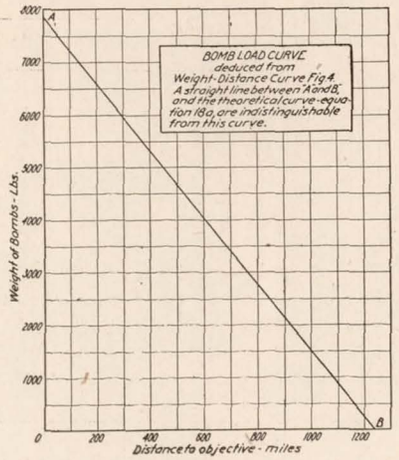


Fig. 6.

CONSEQUENCES OF FLYING AT MAXIMUM SPEED.

In Table 2a the results for flight at maximum speed are tabulated. The gas consumption is constant and the speed of advance was found to be constant to within about 1 per cent. The average value, 106.2 miles per hour was, therefore, used in the computations.

The weight-distance curve (fig. 4) is a straight line, as the fuel consumption and speed are very approximately constant.

The maximum range is considerably less than under greatest range conditions. The difference is 740 miles. A considerable gain in range is thus attained by flying at the proper angle and hence at proper speed.

The useful loads for maximum speed are considerably less than under best range conditions. For an objective 600 miles away the best conditions give a possible load of 4,050 pounds while at maximum speed this is reduced to 2,430 pounds, a reduction of 1,620 pounds.

For convenience, a comparison of the loads and ranges corresponding to them is made in the following tables:

TABLE 4.

Hours of fuel full open.	Bombing load in pounds.	Range at maximum speed.		Range at best speed.		Difference in miles.	
		Total.	Objective.	Total.	Objective.	Total.	Objective.
10	3,070	1,060	530	1,510	755	450	225
7½	4,270	790	395	1,130	565	340	170
4	5,950	420	210	610	305	190	95

TABLE 5.

Hours of fuel full open.	Range.		Bombing load maximum speed.	Bombing load best speed.	Difference in pounds.
	Total.	Objective.			
10	1,510	755	1,030	3,070	2,040
7½	1,130	565	2,738	4,270	1,532
4	610	305	5,090	5,950	860

For the shorter flights the differences decrease but they are considerable in all cases. The bombing load is increased by almost 190 per cent for maximum range speeds over maximum speed conditions for 10 hours fuel.

FLYING AT MINIMUM POWER.

The gas consumption at minimum power is practically identical with that at best range power. While the minimum power is slightly less than the power for best range speed, the speed is also less and the propeller efficiency is also slightly less. The net result is that the time of flight is about the same and the maximum range is diminished.

A calculation of the range at minimum power gives 2,400 miles instead of 2,480 miles.

For flight at minimum power the angle of attack is practically constant and slightly greater than that for best range speed.

TIME REQUIRED FOR ANY RANGE.

For convenience, the curves of elapsed time for any distance flown are given in figure 4 for both best range speeds and maximum speed conditions. By means of them the time of going and returning from any given objective may be read off. In particular it is seen that the maximum time of flight under high speed is 16.4 hours as against 38.0 hours for best range speed.

For a bombing raid on an objective at 600 miles, the total elapsed time to go and return is for maximum speed 11.25 hours and for best range speed 18.65 hours. It will be seen in the following how this time difference may be decreased by flying at high altitudes without changing the efficiency for best range conditions.

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REPORT NO. 69.

PART II.

THEORETICAL ANALYSIS.

By J. G. COFFIN.

THEORY OF MAXIMUM RANGE CONDITIONS.

Notation:

W = weight of machine at any time.
W_f = weight of machine fully loaded with fuel.
W_e = weight of machine empty of fuel.
T = thrust of propeller.
η = efficiency of propeller.
A = supporting wing area.
V = speed of flight.
L = lift per unit wing area per unit speed at ground level.
D = drift per unit wing area under same conditions.
R = parasite resistance per unit wing area under same conditions and is assumed constant.
L and D depend only on the flying angle of attack.
s = distance traversed in time t.
S = range.
$\gamma = \rho/\rho_o$ = ratio of the density of the air at height h to its density at ground level.
c = pounds of fuel (gas and oil) per brake horsepower hour consumed by motors.
$a = \frac{c}{u}$ = pounds of fuel per useful horsepower hour delivered by propeller.

The lift coefficient K_y, as usually given, is proportional to the density, and we may, therefore write

$$K_y = k_y\rho = (k_y\rho_o)\rho/\rho_o = L\gamma$$

where L is the value of K_y at ground level.

The fundamental equations for horizontal flight of the airplane are

$$W = L\gamma AV^2 \tag{1}$$

$$L = D\gamma AV^2 + R\gamma AV^2 = (D+R)\gamma AV^2 \tag{2}$$

CONDITION FOR MINIMUM WORK.

The work done in flying a distance dl against a total drag T is Tdl. The total work done in flying a given distance s is, therefore,

$$\text{Work} = \int_0^s T\,dl$$

This work integral is evidently a minimum if T is always at its least possible value

From equations (1) and (2) we get by division

$$T = W\left(\frac{D+R}{L}\right) \tag{3}$$

This equation shows, since γ has disappeared, that for a constant angle of attack and given weight the thrust is independent of the height at which the flight takes place, and also that for a constant angle of attack the thrust is proportional to the total weight.

It is for the first reason that no mention of altitude was made in Part I. The second statement is verified in figure 2, which plainly shows very approximate proportionality at all actual flying speeds.

It is convenient to employ the polar diagram in the following: This kind of diagram deserves greater popularity than it has yet received in aeronautical calculations in the United States. It consists in plotting L as ordinates against D as abscissae. Any point M on the curve corresponds to a given L and D and hence to a given angle of attack. This angle of attack is marked on the curve.

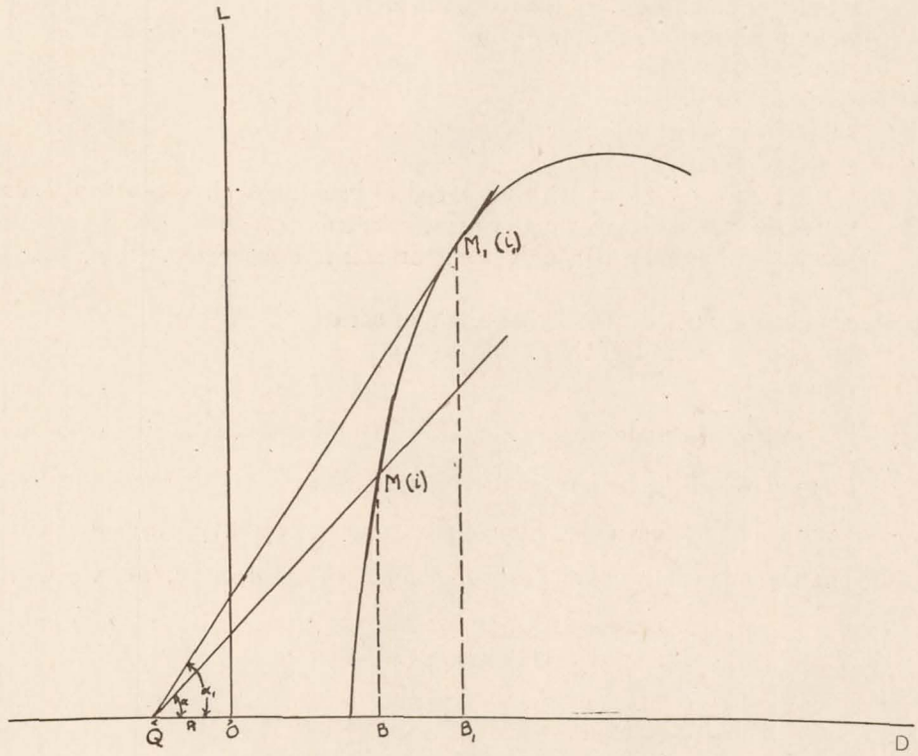


Fig. 7.

Lay off from O the distance OQ equal to R.

Then for any point M, OB = D, MB = L, and OQ = R.

The slope of the line $QM = \frac{L}{D+R} = \tan \alpha$

Consider equation (3). For a given weight and variable values of L and D, that is, for variable angles of attack, let us find the condition for minimum thrust.

$$dT = 0 = \frac{L\,(dD) - (D+R)\,dL}{L^2}$$

As L can not be infinite, the condition is

$$\frac{dL}{dD} = \frac{L}{D+R} \tag{4}$$

That is to say, for minimum thrust the tangent to the polar curve must have a value $\frac{L}{D+R}$. Looking at the polar diagram it is seen that the line QM_1 tangent at M_1 fulfills this condition and corresponds to a given angle of attack i_1. Since the polar is a given curve for the machine, it follows that

(*a*) for minimum thrust the machine must fly at a constant angle of incidence throughout the whole flight whatever the loading may be, and

(*b*) that these minimum thrusts are independent of altitude of flight.

In Part I, Table 2*b*, the angles of incidence corresponding to the least drag have been tabulated. They are remarkably constant, their average deviation from the mean 5.33° being only 0.12° and the greatest difference 0.3°.

For best range speeds, then, it follows that

$$W = C_1 \gamma V^2 \text{ where } C_1 = LA \tag{5}$$

and

$$T = C_2 \gamma V^2 \text{ where } C_2 = (D+R)\,A \tag{6}$$

where C_1 and C_2 are constants for flight at *any* constant angle of incidence. In particular for maximum range conditions they have the values corresponding to the maximum value of $\frac{L}{D+R}$ for the machine.

Let us suppose that the machine loses weight gradually due to fuel consumption alone. If the weight-distance curve can be deduced, the problem of bombing loads and ranges is solved, as explained in Part I.

DEDUCTION OF THE WEIGHT-TIME EQUATION.

Assume that the range of speeds is such that the engine runs at constant efficiency, burning "*a*" pounds of fuel per horsepower hour delivered by the propeller. If c = pounds of fuel consumed per brake horsepower hour and the propeller efficiency is denoted by η, then the fuel consumed per horsepower hour delivered by the propeller is given by $a = \frac{c}{\eta}$

The power at any speed is

$$TV = C_2 \gamma V^2 . V = C_2 \gamma \left(\frac{W}{C_1 \gamma}\right)^{3/2} = \frac{1}{\sqrt{\gamma}} \frac{C_2}{C_1^{3/2}} W^{3/2} \tag{7}$$

The rate of fuel consumption is aTV and in time dt a weight $a\,T\,V\,dt$ of fuel will be consumed, hence

$$a\,TV\,dt = \frac{1}{\sqrt{\gamma}} \frac{aC_2}{C_1^{3/2}} W^{3/2} dt = -dW \tag{8}$$

where $-dW$ is the loss of weight of the plane in time dt.

The weight of the plane at any time t is therefore, if W_f is the weight full,

$$W = W_f - \frac{a}{\sqrt{\gamma}} \frac{C_2}{C_1^{3/2}} \int_o^t W^{3/2} dt \tag{9}$$

Equation (8) is a differential equation for W at any time, and may be written

$$\frac{dW}{W^{3/2}} = -\frac{a}{\sqrt{\gamma}} \frac{C_2}{C_1^{3/2}} dt = -K dt \tag{10}$$

$$\text{where } K = \frac{a}{\sqrt{\gamma}} \frac{C_2}{C_1^{3/2}} \tag{11}$$

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Solving and determining the constant of integration by the condition that when $t=0$, $W=W_f$, we get

$$\frac{1}{\sqrt{W}}=\frac{K}{2}t+\frac{1}{\sqrt{W_f}} \tag{12}$$

This equation is the desired relation between W and t and shows how the load diminishes as t increases. Since K contains γ, the rate of diminution of load depends upon the altitude.

The time of maximum flight can be obtained by letting W_f decrease to W_e, the weight of the empty machine.

$$t_{max}=\frac{2}{K}\left(\frac{1}{\sqrt{W_e}}-\frac{1}{\sqrt{W_f}}\right) \tag{13}$$

This maximum time of flight computed with equation (13), using 1.03 pounds per horsepower hour as the average fuel consumption, gives a value of $t_{max}=38.3$ hours, as compared with $t_{max}=38.0$ hours as taken from the time-weight curve in figure 4. The two methods again check very well. The formula arranged to give the time in hours is, for low levels,

$$t\ (\text{hours})=10550\left(\frac{1}{\sqrt{W_e^{\#}}}-\frac{1}{\sqrt{W_f^{\#}}}\right)$$

This time of flight diminishes proportionally to $\sqrt{\gamma}$.

DEDUCTION OF THE DISTANCE-TIME EQUATION.

The distance traversed in time dt is, using (5).

$$ds=V\,dt=\sqrt{\frac{W}{C_1\gamma}}\,dt$$

so that in time t

$$s=\frac{1}{\sqrt{C_1\gamma}}\int_0^t\sqrt{W}\,dt$$

which becomes, using (12),

$$s=\frac{2}{K}\frac{1}{\sqrt{C_1\gamma}}\int_0^t\frac{\frac{K}{2}\,dt}{\frac{K}{2}t+\frac{1}{\sqrt{W_f}}}$$

Integrating and determining the constant by the condition that when $t=0$, $s=0$, we get

$$s=\frac{2}{K}\frac{1}{\sqrt{C_1\gamma}}\log\frac{K/_2t+\frac{1}{\sqrt{W_f}}}{\frac{1}{\sqrt{W_f}}} \tag{14}$$

This equation is the desired relation between the distance flown and the time. The distance increases with the time and depends upon the altitude of flight. For a given time interval the distance flown increases proportionally to $\frac{1}{\sqrt{\gamma}}$.

DETERMINATION OF THE WEIGHT-DISTANCE EQUATION.

Eliminate t between equations (12) and (14):

$$s=\frac{2}{K}\frac{1}{\sqrt{C_1\gamma}}\log\frac{\frac{1}{\sqrt{W}}}{\frac{1}{\sqrt{W_f}}}=\frac{1}{K\sqrt{C_1\gamma}}\log\frac{W_f}{W} \tag{15}$$

where

$$\frac{1}{K\sqrt{C_1\gamma}}=\frac{\sqrt{\gamma}C_1^{3/2}}{aC_2\sqrt{C_1\gamma}}=\frac{C_1}{aC_2}=\frac{1}{a}\cdot\frac{L}{D+R} \tag{16}$$

So that finally

$$s=\frac{1}{a}\cdot\frac{L}{D+R}\cdot\log\frac{W_f}{W}$$

Or, more specifically in terms of c and n,

$$s=\frac{\eta}{c}\frac{L}{D+R}\cdot\log\frac{W_f}{W} \tag{17}$$

This equation is true for any condition of flight at constant angle of incidence, where the ratio $\frac{L}{D+R}$ remains constant. For maximum range the maximum value of $\frac{L}{D+R}$ is of course used. This equation shows that as W diminishes s increases, and that the *distance* flown is independent of the flying altitude, since γ has disappeared.

The maximum range S can be obtained by finding the value of s for $W=W_e$.

Assume $W_f=15{,}000$ pounds.
$W_e=7{,}130$ pounds.

$$\text{Max.}\left(\frac{L}{D+R}\right)=9.2$$

$$S=2{,}480 \text{ miles.}$$

We obtain for "a" a value of 1.03 pounds per horsepower hour.
This value checks very well with $a=1.033$ pounds per horsepower hour, the average value used in the preceding greatest range calculations, in P art I.This check is very satisfactory and shows that the two methods are in good agreement.

EQUATION CONNECTING USEFUL LOAD AND OBJECTIVE DISTANCE.

If we let $b=\frac{1}{a}\frac{L}{D+R}$ equation 17 becomes

$$s=b\log\frac{W_f}{W}$$

and hence

$$W=W_fe^{-s/b} \tag{18}$$

Considering Fig. 5 it is easy to see that the load B for any given objective at distance s is evidently, if S = max. range

$$B=W_s-W_{S-s}=W_f(e^{-s/b}-e^{-(S-s)/b}) \tag{19}$$

and since $W_e=W_fe^{-S/b}$ this becomes

$$B=W_fe^{-s/b}-W_ee^{s/b} \tag{20}$$

We can thus compute the useful load for any objective. If the weight distance curve is plotted, however, it seems easier to plot the curve represented by (20) by the method explained above.

PROOF THAT LOAD-OBJECTIVE CURVE IS STRAIGHT.

In Part I the curve between useful load and distance to objective (Fig 6) was very approximately a straight line. The equation for this curve is

$$B = W_f(e^{-s/b} - e^{-(S-s)/b}) \tag{19}$$

where S is the maximum range, and s/b is a quantity which is smaller than unity and generally less than $\frac{1}{2}$.

This is not the equation of a straight line but turns out to be very closely straight as seen by the following:

Let $x = \frac{s}{b}$, $x_1 = \frac{S}{b}$ for the moment.

Expanding the exponentials and neglecting *cubes* and higher powers of x, we have

$$e^{-x} - e^{-(x_1-x)} = 1 - x + \frac{x^2}{2} - \left[1 - (x_1 - x) + \frac{(x_1-x)^2}{2}\right]$$

$$= (2 - x_1)\left(-x + \frac{x_1}{2}\right) \qquad \text{a linear relation.}$$

The second powers have completely canceled.

Therefore

$$B = \frac{W_f}{b}\left(2 - \frac{S}{b}\right)\left(-s + \frac{S}{2}\right) \tag{21}$$

When

$$s = \frac{S}{2} \qquad B = o$$

When

$$s = o \qquad B = \frac{W_f}{b}\left(2 - \frac{S}{b}\right)\frac{S}{2}$$

But

$$W_f - W_e = W_f(1 - e^{-S/B}) = W_f\left(1 - 1 + \frac{S}{b} - \frac{S^2}{2b^2}\right) = \frac{W_f}{b}\left(2 - \frac{S}{b}\right)\frac{S}{2}$$

so that the straight line (20) passes through A and B as it should.

The curve then is a straight line to a high approximation and can always be taken as such.

EFFECT OF CLIMB AT START AND GLIDE AT END OF FLIGHT.

If the flight is so made that the plane is allowed to climb steadily as the load decreases, it must, of course, come down at the end of the flight when all the fuel is exhausted. The potential energy put into the plane by the consumption of a certain amount of fuel is then partially reemployed in the descent. A slight calculation shows that it is puerile to consider this effect, as shown below.

Assume that the plane rises under power to a height h with full fuel load and at the end of the flight descends with power shut off and without fuel. The potential energy which can not be regained is hence approximately the work done in raising the total weight of fuel to the maximum height reached. As shown previously, the expenditure of fuel is about 1 pound per horsepower-hour delivered by the propeller, which is equivalent to

$$550 \times 60 \times 60 = 1{,}980{,}000 \text{ foot-pounds of energy per pound of fuel.}$$

Assume 50 per cent useful load (all fuel), the work required to raise the plane to a height h is

$$\frac{W}{2} \times h \text{ foot-pounds,}$$

which is a considerably overestimated value, as the climb is gradual, and the *total* fuel load is not raised to the maximum height.

Considering the specific machine used in Part I, the work done in raising 7,500 pounds of fuel to a height of 10,000 feet, say, is 75,000,000 foot-pounds. This amount of work would require

$$\frac{75{,}000{,}000}{1{,}980{,}000} = 38 \text{ pounds} = 6.3 \text{ gallons of fuel}$$

(gas and oil), assuming 6 pounds to the gallon. As the total load is 1,250 gallons, this amount is about one-half of 1 per cent of the total fuel load, which is quite negligible in calculations of this nature.

As the percentage amount for any other type of machine would be about the same, we have made no effort to take this theoretically interesting part of the subject into consideration.

PRACTICAL SIMPLIFIED METHOD OF APPLYING THIS THEORY TO A SPECIFIC CASE.

The application of this theory to any specific case now reduces to the greatest simplicity as follows:

Data required. W_f = weight fully loaded with fuel
W_e = weight empty of fuel.
i_1 = angle of incidence for minimum total resistance.

1. Calculate the maximum range for an all fuel load by equation 17

$$S = \frac{\eta}{c}\left(\frac{L}{D+R}\right)_{max.} \log_e \frac{W_f}{W_e}$$

and plot the value of S/2 as abscissa for an ordinate B = o.

2. Plot $W_f - W_e$ as an ordinate for S = o.

3. Connect these two points by a straight line and we have a diagram similar to the following figure:

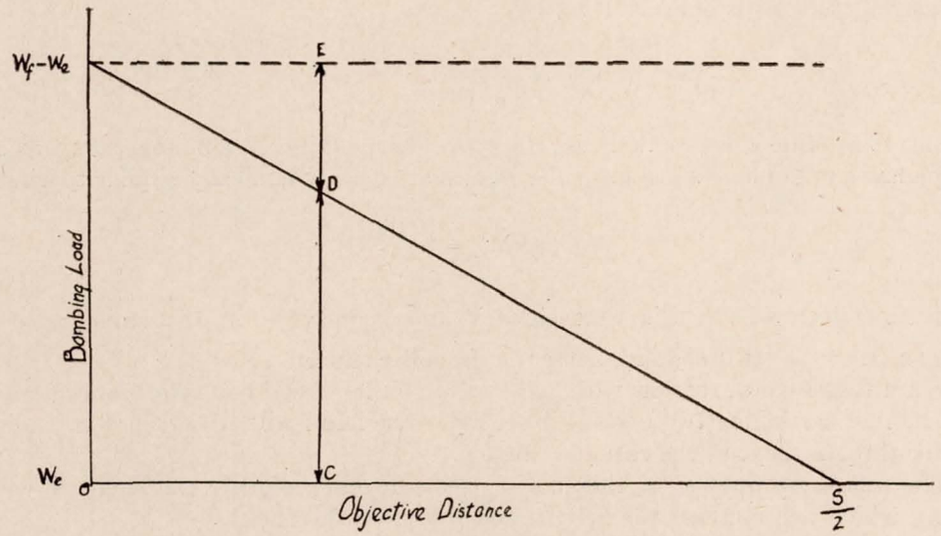


Fig. 8.

Any ordinate such as CD will give the maximum pounds of load that can be carried for an objective at distance OC. The distance DE will give the corresponding weight of gasoline to be carried. (See Fig. 6.)

For usual machines

$$S \text{ (miles)} = 375 \frac{2.30}{1.03}\left(\frac{L}{D+R}\right)_{max.} \log_{10}\left(\frac{W_f}{W_e}\right) \qquad (22)$$

EFFECT OF ALTITUDE ON SPEED, POWER, AND TIME.

From equation (5) it follows that for a given weight the speed must increase as γ diminishes and the exact relation is

$$V_h = \frac{V_o}{\sqrt{\gamma}} \tag{23}$$

where h is the height characterized by γ. From equation (7) it follows that the power required for flight increases in the same proporation as the speed so that

$$P_h = \frac{P_o}{\sqrt{\gamma}} \tag{24}$$

This is otherwise evident as the thrust does not change.

From the latest experimental tests of motor horsepower and motor efficiency at altitudes, it is found that the power falls off almost in proportion to the density so that

$$P_h' = P_o'\gamma \tag{25}$$

Hence, to fly at an altitude characterized by γ, a power P_o' at the ground, which becomes $P_o'\gamma$ at the height, corresponding to γ, must be provided, such that

$$P_o'\gamma = \frac{P_o}{\sqrt{\gamma}} \tag{26}$$

If the maximum available horsepower P_o max. at the ground is provided, the plane will rise until

$$P_o \text{ max. } \gamma = \frac{P_o}{\sqrt{\gamma}} \tag{27}$$

or to such an altitude as is characterized by

$$\gamma = \left(\frac{P_o}{P_o \text{max.}}\right)^{2/3} \tag{28}$$

In order to provide a constant thrust the propeller must increase in angular speed according to the same law as the plane since propeller blades are aerodynamically similar to wings, so that

$$n = (\text{RPM})_h = \frac{(\text{RPM})_o}{\sqrt{\gamma}} \tag{29}$$

It follows immediately from this that since V and n increase in the same ratio then $\frac{V}{nD}$ remains constant with altitude, and hence the propeller efficiency.

There are thus several reasons why flight at a high level will be better than at low.

(*a*) The motor running full open will probably use less fuel per horsepower than has been assumed for throttle, say, in the ratio of 0.6 to 0.7.

(*b*) The motor running at a higher speed can develop slightly more power with proper adjustment, which will increase the height, and therefore the speed.

(*c*) A very good third reason is that the duration of the flight will be considerably lessened and this, together with

(*d*) the increased safety due to high altitude and greater flying speed lead to the conclusion that: For bombing purposes the aviator should fly at a certain predetermined constant angle of attack; he should allow the plane to rise as the load diminishes.

Since the work consumed in rising to the higher level is at least partially returned when the machine glides down at the end of the trip without power, these works have not been considered.

The aviator will thus attain the greatest range, carry the greatest load, secure the greatest safety and speed consistent with these conditions and ecomomize in time as well.

NOTE ON CEILINGS.

By employing the equation (28):

$$\gamma=\left(\frac{P_o}{P_o \text{ max.}}\right)^{2/3}$$

based upon the assumption $P_h = P_o\gamma$, the ceiling for any corresponding weight of machine may be found if the available and required horsepower is known.

The following table of computations refers to the machine considered in Part I.

Table of ceiling computations.

Weight in pounds.	Available horsepower P_m.	Required horsepower P_o.	$\frac{P_o{}^{2/3}}{P_m}$.	Ceiling.	
				(*a*)	(*b*)
15,000	600	320	0.658	12,500	10,350
13,000	582	265	.592	16,000	13,900
11,000	555	212	.527	19,600	17,900
9,000	518	159	.455	23,800	21,800
7,000	477	107	.368	29,600	25,600

The column (*a*) under the heading of ceiling in the above table has been obtained from a γ-altitude curve based upon data obtained from report No. 14 of the National Advisory Committee for Aeronautics.

The column (*b*) under "Ceiling" has been obtained from data on the average performance values of a number of machines.

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REPORT NO. 69.

PART III.

EFFECT OF WIND ON RANGE CALCULATIONS.

By J. G. Coffin. *September 1, 1919.*

BEST FLIGHT SPEED.

If there is a retarding or a helping wind it will be shown below that the conditions for maximum range must be changed.

The following is a proof of an important method for finding the proper attitude of flight with or without winds.

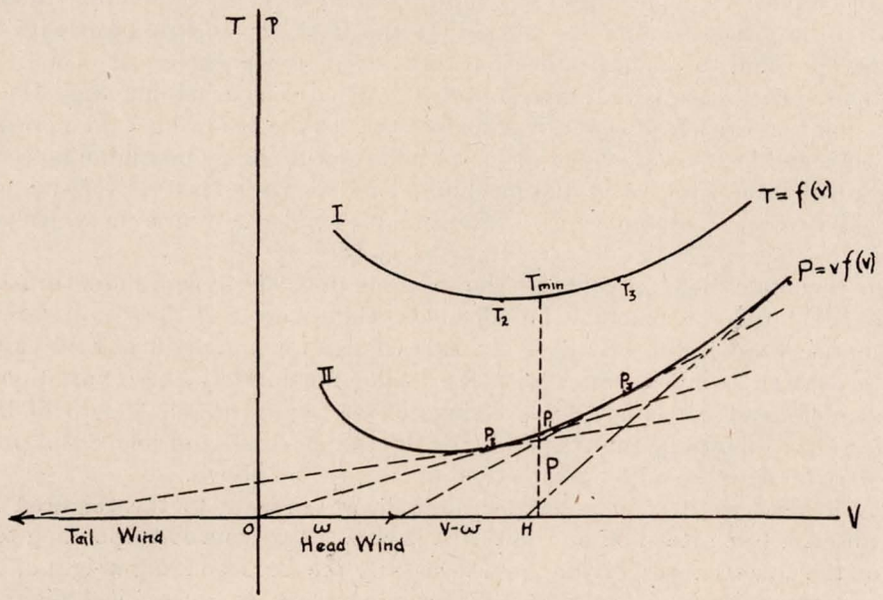


Fig. 9.

Let curve I be the required thrust-speed curve and II the required power-speed curve for the machine.

Consider a machine of constant weight W which is flying with air speed V against a wind speed w. The ground speed is then $V-w$.

In order to fly a *ground* distance ds it will take a time $dt=\frac{ds}{V-w}$.

If the thrust is T and "a" is the rate of gas consumption per *delivered* power the gas consumed in flying this distance is

$$aPdt=aP\frac{ds}{V-w} \tag{30}$$

As "a" is assumed constant and ds is fixed, for this expression to be a minimum we must have

$$\frac{d}{dV}\frac{P}{V-w}=O=\frac{(V-w)\ P'-P}{(V-w)^2}$$

and since $V-w$ can not be infinite the condition is:

$$P'=\frac{P}{V-w}$$

This means that the subtangent to the power-speed curve is $(V-w)$ and the equation is fulfilled by the following construction: Lay off w, figure 9, on the V-axis, to the right of the origin, if a contrary wind, or to the left if a following wind, and draw a tangent from this point to the P–V curve; it is seen that the slope or tangent P′ is equal to $\frac{P}{V-w}$. For calm air the tangent is drawn from the origin. As the slope of a line drawn from the *origin* to any point on the P–V curve is always $\frac{P}{V}=\frac{VT}{V}=T$ it follows that the thrust varies as the slope of such a line, and as the tangent from the origin to the P–V curve has evidently the minimum slope, this shows that in calm air the machine must fly at minimum thrust, as is otherwise evident.

Thus the minimum points of the T–V curves lie directly over the points of tangency of lines from the origin to the P–V curves.

If there is a head wind this condition of minimum thrust no longer holds and more power is required for most economic flight which corresponds, of course, to a greater thrust.

As the power curve is limited to the right by the maximum output of the power plant it is seen that for *economical* flight there is a limiting head wind corresponding to the distance OH, where H is the intersection of the tangent to the P–V curve at its limit with the V-axis. It is, of course, possible to make headway against stronger winds, but the condition for economical flight in such a case is no longer fulfilled. When w is a helping wind the tangent is drawn from a point on the left of O and it is evident that as the following wind increases in speed it pays to use less and less power, the limit for an infinite wind being minimum power. In other words, it pays to let the wind carry the machine along with the least use of the power plant. Curiously enough, this corresponds to a thrust greater than the minimum which is proper in calm air.

While for economic flight in calm air the machine must fly at minimum thrust and hence at maximum L/D [1] for the machine for all loads, this simplicity does not obtain for economic flight in the wind. Not only does the L/D change for a given load with varying winds, but also for a constant wind it varies with the load. Fortunately these variations are small for any reasonable head winds and for a change of load equal to the weight of the machine empty. Referring to figure 9, the proper L/D's for the machine and hence the proper angles of incidence may be determined by the method demonstrated above.

Assuming a head wind of w miles per hour draw tangents to the required horsepower curves from abscissa $+w$. Read off on the thrust curves the thrusts corresponding to the points of tangency on the power curves, divide these thrusts by the corresponding weight of the machine and the values thus obtained are the D/L's corresponding to economical flight under the assumed conditions.

SINGLE CURVE METHOD.

A much simpler method will now be described to accomplish the same result requiring the drawing of but a single curve for the whole procedure.

The method is based upon the following considerations:

The equations for horizontal flight may be written

$$W=LAV^2$$
$$T=DAV^2$$
$$P=TV$$

From these we obtain

$$V=\frac{1}{\sqrt{LA}}\cdot W^{1/2} \tag{31}$$

$$T=\frac{D}{L}\cdot W \tag{32}$$

$$P=\frac{1}{\sqrt{LA}}\cdot\frac{D}{L}W^{3/2} \tag{33}$$

[1] In the following D represents the total drag on the machine and corresponds to (D+R) in the preceding pages.

These equations show that as the load changes the corresponding speeds for any given angle of incidence vary as $W^{1/2}$, the thrusts as W and the powers as $W^{3/2}$.

Consider now any required power-speed curve. Figure (9).

The required power curves for any other weight W_1 can be calculated from this given curve by multiplying the speeds by $\left(\frac{W_1}{W}\right)^{1/2}=\lambda^{1/2}$ and the corresponding powers by $\left(\frac{W_1}{W}\right)^{3/2}=\lambda^{3/2}$ and plotting these values on the same sheet. If required the thrust curves can be obtained by plotting $\frac{P\lambda^{3/2}}{V\lambda^{1/2}}=\frac{P}{V}\lambda$ against $V^{1/2}$.

Consider what effect a change in loading has upon the equation of condition for economical flight.

$$\frac{dP}{dV}=\frac{P}{V-w}$$

becomes for a new loading W_1

$$\frac{dP\cdot\lambda^{3/2}}{dV\cdot\lambda^{1/2}}=\frac{P\lambda^{3/2}}{V\lambda^{1/2}-w}$$

where

$$\lambda=\frac{W_1}{W}$$

This reduces to

$$\left(\frac{dP}{dV}\right)=\frac{P}{V-\frac{w}{\lambda^{1/2}}} \tag{34}$$

which indicates that instead of plotting P – V curves for various loads and drawing tangents from the abscissa w it is sufficient to plot but one curve, and as the load increases draw tangents from abscissas $\frac{w}{\lambda^{1/2}}$ as the *load* changes. The point of tangency determines values of P and V which correspond to a required power $P\ \lambda^{3/2}$ and a flying speed $V\ \lambda^{1/2}$ for the new condition.

As the main interest here is to find the variations in L/D, or, what is the same thing, in D/L we continue as follows:

Since $\frac{P\lambda^{3/2}}{V\lambda^{1/2}}=\frac{P\lambda}{V}$ is the new corresponding thrust, and since the new thrust divided by the new load W_1 gives the new D/L, it is seen that

$$\frac{\frac{P}{V}\lambda}{W_1}=\frac{T\lambda}{W_1}=\frac{T}{W}=\left(\frac{D}{L}\right)_1 \tag{35}$$

and hence in order to determine the D/L for any new loading it is merely necessary to draw a tangent from $\frac{w}{\lambda^{1/2}}$, and the ratio $\frac{P}{V}$ read off on the *original* scale is the corresponding value of the $\frac{D}{L}$ required.

This single curve is preferably plotted for some simple load such as 1,000 pounds or 10,000 pounds. The D/L's will then come out directly by dividing the power by the speed, and by changing the position of the decimal point.

EXAMPLE OF USE OF THE ONE-CURVE METHOD.

In order to check the proposed method against the usual multicurve method, three P-V curves were plotted for the same machine with loads of 7,000 pounds, 10,000 pounds, and 13,000 pounds, respectively. The machine weighs 7,000 pounds empty.

These curves are shown in Fig. (10). The L/D's for various wind speeds were derived from them and compared with the L/D's taken from the 10,000-pound curve using modified wind speeds as described above.

The agreement is very satisfactory, as shown in the table (6) below.

When using the curve for a 7,000-pound load the modified wind speeds corresponding to w are

$$w\sqrt{\frac{10}{7}}=1.195\ w,$$

and for a load of 13,000 pounds they are

$$w\sqrt{\frac{10}{13}}=.877\ w$$

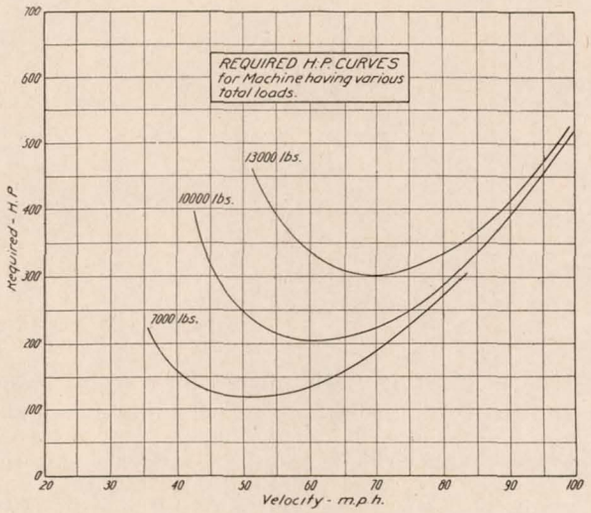


Fig. 10.

TABLE (6).

Actual wind speeds, w, in miles per hour.	L/D from 7,000-pound P-V curve.	L/D from 10,000-pound P-V curve.	Modified wind speeds used, 1.195 w.	L/D direct from 10,000-pound curve.	L/D from 13,000-pound P-V curve.	L/D from 10,000-pound P-V curve.	Modified wind speeds used, 0.877 w.
		(7,000 pounds.)		*(10,000 pounds.)*		*(13,000 pounds.)*	
−40	8.26	8.31	−47.80	8.31	8.35	8.33	−35.06
−20	8.35	8.37	−23.90	8.35	8.38	8.40	−17.53
0	8.41	8.43	0	8.44	8.43	8.43	0
10	8.41	8.43	11.95	8.41	8.41	8.42	8.77
20	8.29	8.31	23.90	8.32	8.41	8.42	17.53
30	8.04	8.03	35.85	8.19	8.25	8.25	26.60
40	7.47	7.45	47.80	7.96	8.04	8.07	35.06
50	5.95	5.90	59.75	7.21	7.62	7.60	43.82

Several interesting results appear from the values obtained.

1. The influence of wind on the L/D is greater for light loads than for heavy. A change in L/D from 8.43 to 5.90 is found for the 7,000-pound machine as against a change from 8.43 to 7.60 for the 13,000-pound machine, these values corresponding to a change in head-wind speed of 50 miles per hour.

2. This influence still holds although much less noticeably for helping winds, the L/D changing from 8.43 to 8.30 for the light machine as against 8.43 to 8.34 for the heavy machine.

3. For any reasonable head wind that could be flown against in long-distance flight, the change in the L/D is small, running from 8.43 to 8.00 for the 7,000-pound case to 8.43 to 8.25 for the 13,000-pound case, these values corresponding to a head wind of 0 and 30 miles per hour respectively.

As practically it is difficult to fly at a given angle with mathematical accuracy the main result of these figures is to show that as the head winds increase in speed it is necessary to slightly diminish the flying angle; exactly how much depending on a preliminary calculation as outlined above.

The instructions to the pilot can be given in either of two ways:

(*a*) Proper flying angles for any given wind.

(*b*) Proper air speed for any given wind.

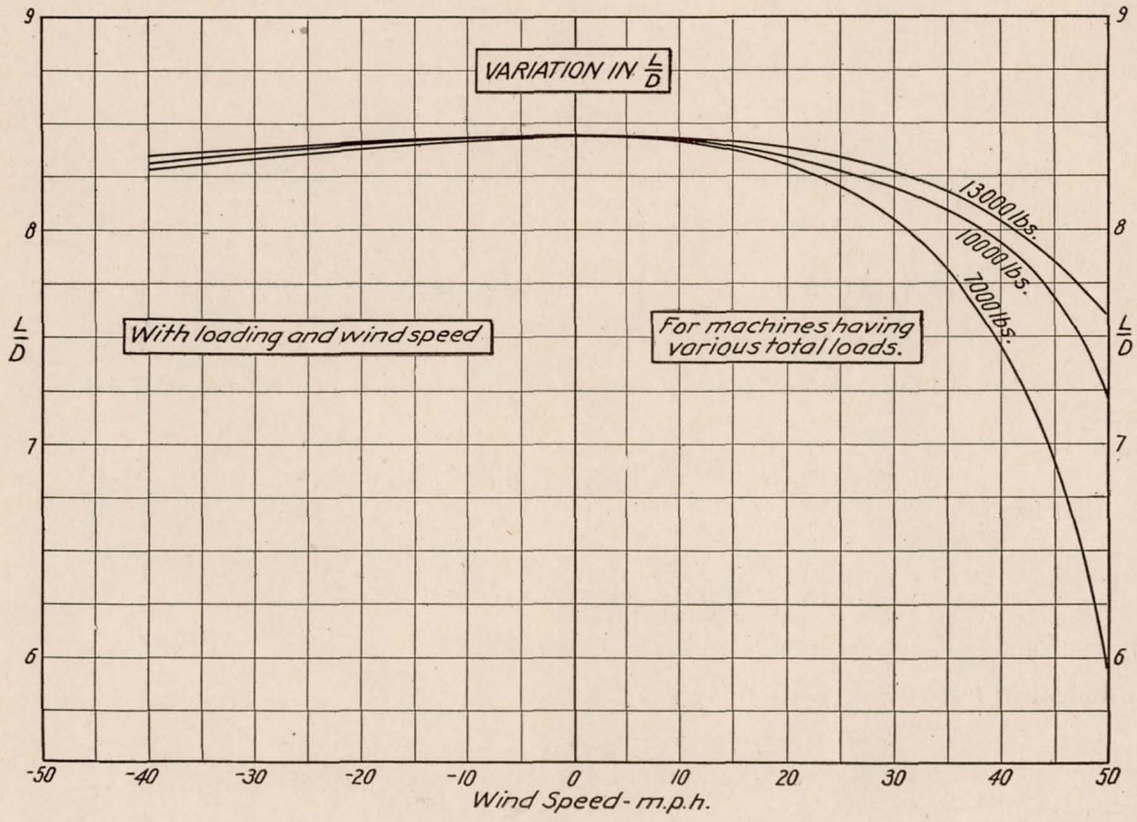


Fig. 11.

A plot of the values of L/D against wind speeds for the three loadings is shown in figure (11). These L/D values correspond to definite air speeds at a given altitude and definite angles of incidence which can also be placed upon the plot. Such a chart will give with sufficient exactness the proper flying angles for practical navigation under economical conditions.

RANGE FORMULÆ INCLUDING EFFECT OF WINDS.

The time-weight equation (13)

$$t = \frac{2}{K}\left(\frac{1}{\sqrt{W}} - \frac{1}{\sqrt{W_f}}\right)$$

Where

$$K = \frac{a}{\sqrt{\gamma}}\frac{C_2}{C_1^{3/2}}$$

is naturally unchanged, since for a given angle of incidence the *time* in which the fuel is consumed can not depend on whether there is a wind or not.

The time-distance equation must be modified. Since the ground distance is the important factor the wind modifies the range. If at any instant the air-speed is V and the wind speed w, the ground speed is $V-w$, and in time dt a ground distance

$$dS=(V-w)dt \tag{36}$$

will be covered. With an obvious substitution, this becomes

$$dS=\sqrt{\frac{W}{C_1\gamma}}\,dt-w\,dt$$

and

$$S=\frac{1}{\sqrt{C_1\gamma}}\int_0^t W^{1/2}\,dt-\int_0^t w\,dt$$

Using equation (13) this becomes

$$S=\frac{1}{\sqrt{C_1\gamma}}\,\frac{2}{K}\int_0^t\frac{\frac{K}{2}\,dt}{\frac{K}{2}\,t+\frac{1}{\sqrt{W_f}}}-w\int_0^t dt=\frac{2}{K}\,\frac{1}{\sqrt{C_1\gamma}}\log_e\left(\frac{K}{2}\,t+\frac{1}{\sqrt{W_f}}\right)-wt+\log C$$

The constant of integration log C is determined by the condition that when $t=0$ $S=0$ and

$$\log C=-\frac{2}{K}\,\frac{1}{\sqrt{C_1\gamma}}\log_e\frac{1}{\sqrt{W_f}}$$

so that finally

$$S=\frac{2}{K}\,\frac{1}{\sqrt{C_1\gamma}}\log_e\frac{\frac{K}{2}\,t+\frac{1}{\sqrt{W_f}}}{\frac{1}{\sqrt{W_f}}}-wt$$

Eliminating t and giving K its value we have

$$S=\frac{1}{a}\left(\frac{L}{D}\right)\log\frac{W_f}{W}-\frac{2}{a}\left(\frac{L}{D}\right)\sqrt{\gamma LA}\left(\frac{1}{\sqrt{W}}-\frac{1}{\sqrt{W_f}}\right)w \tag{37}$$

The L/D which appears in this equation is an average value given by the preliminary calculation as in Table (6) corresponding to loads and wind speeds for which the range is desired.

It would, of course, be possible to introduce an empirical expression for L/D in terms of W which could be integrated, but no practical advantage would accrue on account of the impossibility of obeying the mathematically exact conditions in actual flight.

The expression (31) for S can be put into either of the following forms by simple transformations:

$$\begin{aligned}S&=\frac{1}{a}\left(\frac{L}{D}\right)\log\frac{W_f}{W}-\frac{2}{a}\left(\frac{L}{D}\right)\left(\frac{1}{V}-\frac{1}{V_f}\right)w\\&=\frac{1}{a}\left(\frac{L}{D}\right)\log\frac{W_f}{W}-wt\\&=\frac{2}{a}\left(\frac{L}{D}\right)\left[\log\frac{V_f}{V}-w\left(\frac{1}{V}-\frac{1}{V_f}\right)\right]\\&=\frac{1}{a}\left(\frac{L}{D}\right)\log\frac{W_f}{W}-\frac{2}{a}\,w\left(\frac{W}{P}-\frac{W_f}{P_f}\right)\end{aligned}$$

In all of these expressions the altitude of flight is assumed to be substantially constant.

SUMMARY.

The relation between useful load and range has been worked out by two distinct methods.

Part I employs no new theory and is made by the usual performance estimate methods. It would involve considerable plotting of curves and is cumbersome.

Part II gives a theoretical solution. This solution checks remarkably well with the previous one in every particular. It leads to an elegant and simple solution for any specific case.

Directions are given for the application of the results of this paper to any machine. The total time required for this complete calculation should not take over 15 minutes.

The results of interest for calm air are:

1. The machine should fly at a constant angle of attack, the angle corresponding to the minimum value of $\frac{\text{Weight}}{\text{Total resistance}}$.

2. It is practically immaterial whether the machine flies high or low as far as range is concerned.

3. There is an advantage in flying high in that the time is much reduced.

4. The resistance is proportional to the weight at a given altitude.

5. The result of flying at maximum speed is a very much diminished range, or for a given range a very much diminished useful load.

6. The result of flying at minimum power is to slightly reduce the range.

7. The times of flight at the same level for flying at best range speed and at minimum power speed are practically the same.

8. The condition for best range is shown.

9. The weight-time curve is deduced.

10. The range-time curve is deduced.

11. The weight-range curve is deduced.

12. The effect of altitude has been taken into account.

13. The time is greatly diminished for flying at corresponding levels.

14. The theory checks closely with the ordinary methods of Part I.

Part III gives a theoretical solution of the effect of wind on range. First, a proof of a method for determining the L/D and air speed for the machine under any wind conditions is given. A new method is shown wherein but one P–V curve is required for any load and any wind speed.

Variations in L/D for changes in load and wind speed are derived and checked against the usual methods.

The weight-distance formula is derived as modified by winds.

The results of interest for flight in winds are:

1. The angle of attack changes but slightly when flying against winds of reasonable strength, and but very slightly when flying with winds of any strength.

2. The altitude of flight affects the range. The reason being that higher speeds are attained at higher altitudes and the ratio of air speed to wind speed changes. However, as wind speeds change with altitude it does not seem worth while to go into the matter more fully.

3. Other things being equal, it is slightly advantageous to fly high, especially as to time of flight.

4. The weight-time curve is unchanged.

5. The range-time curve is deduced.

6. The weight-range curve is deduced.

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REPORT No. 70

PRELIMINARY REPORT ON FREE FLIGHT TESTS

BY

E. P. WARNER AND F. H. NORTON

Aerodynamical Laboratory, National Advisory Committee for Aeronautics, Langley Field, Va.

153215—S. Doc. 166, 66–2——39

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REPORT NO. 70.

PRELIMINARY REPORT ON FREE FLIGHT TESTS.

By Edward P. Warner and F. H. Norton.

DESCRIPTION OF AIRPLANE EMPLOYED.

In a series of tests which have been made by the advisory committee's staff at Langley Field during the summer of 1919 with the objects of determining the characteristics of airplanes in flight and the extent to which the actual characteristics differ from those predicted from tests on models in the wind tunnel, and of studying the balance of the machines and the forces which must be applied to the controls in order to maintain longitudinal equilibrium, two airplanes have been employed. Both are advanced training machines of the JN4H type and both are equipped with Hispano-Suiza 150 horsepower engines, but they are somewhat different in structural details. The most important differences in connection with the aerodynamic characteristics of the airplanes are the use of an oil radiator suspended below the body and a reserve gasoline tank mounted in the center section of the upper wing on one of the machines, these accessories being lacking on the other. The machine carrying the oil radiator and the reserve tank will be referred to in this report as No. 1, the other as No. 2. In addition to the differences just noted, airplane No. 1 had the aluminum doors in the sides of the body just forward of the wings, removed in order to permit of a freer flow of air through the radiator and past the engine, while No. 2 was flown with these doors in place. No cowling over the upper part of the engine was used on either machine, this being freely exposed to the air in order to dissipate as much heat as possible directly to the slip stream as it passed over the cylinder heads. Despite all precautionary measures adopted to prevent overheating, great difficulty was experienced in keeping the engine cool during the summer, and it was seldom possible to climb with the throttle fully open for more than a few minutes without raising the water temperature dangerously near the boiling point.

The two machines used are shown in figure 1, and general arrangement drawings of the JN4H are given in figure 2. The more important areas and the weights are tabulated below:

Areas.	Square feet.
Upper main plane, including ailerons	203.0
Lower main plane	150.0
Ailerons (total)	34.6
Stabilizer	28.5
Elevators	21.8
Fin	3.7
Rudder	11.8
Weights.	**Pounds.**
Airplane No. 1, tanks and radiator full, seats empty	1,906
Airplane No. 2, tanks and radiator full, seats empty	1,844

The difference in weight is due to the larger amount of gasoline and oil carried by No. 1 and to the extra tank and oil radiator provided on that machine.

The propellers used on the two machines were nominally exactly alike, both being made from the Air Service's design No. 13,279, having a diameter of 8 feet 6 inches, and being designed for an effective pitch of 5.22 feet. Actually they were quite different, the propeller which was used on machine No. 2 in most of the work having warped so that the pitch was

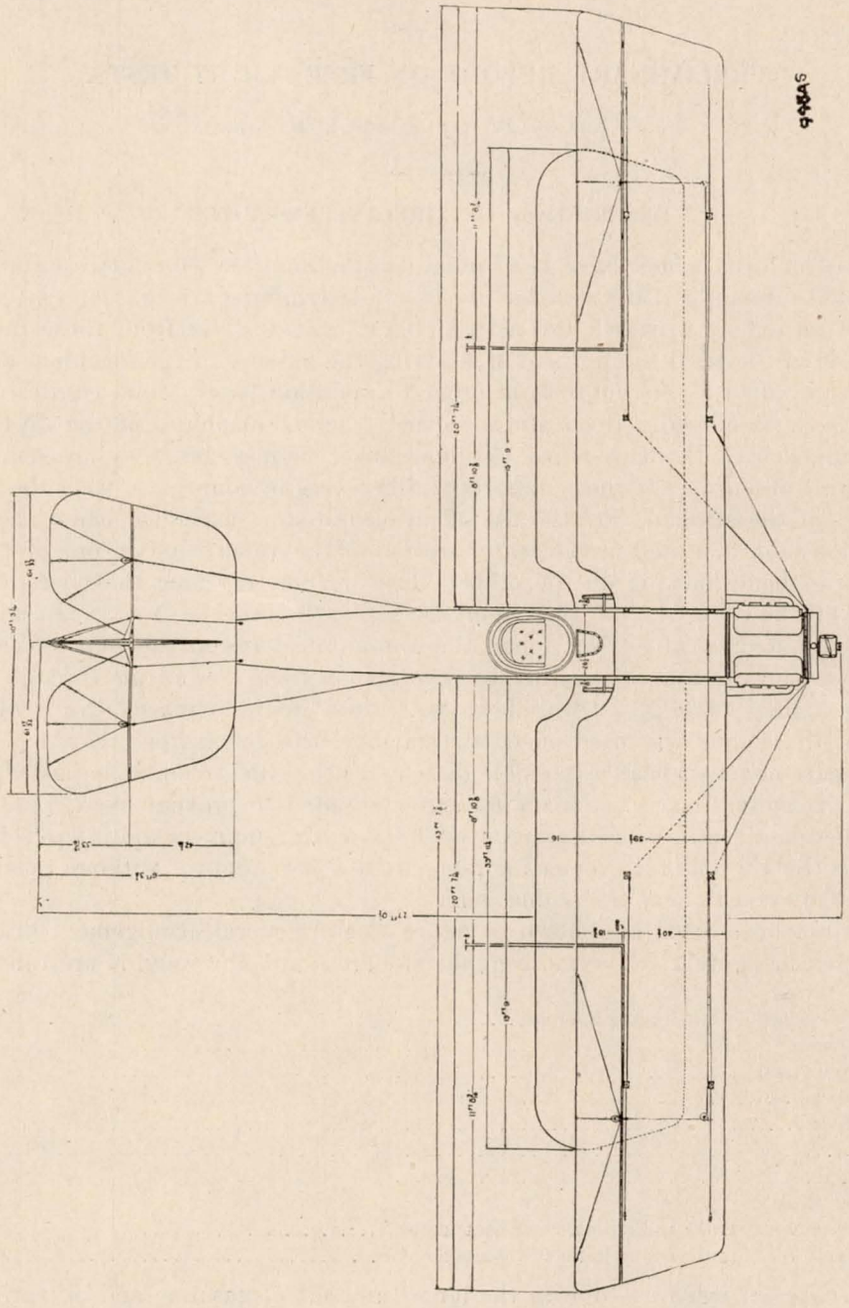


FIGURE 2 (a).

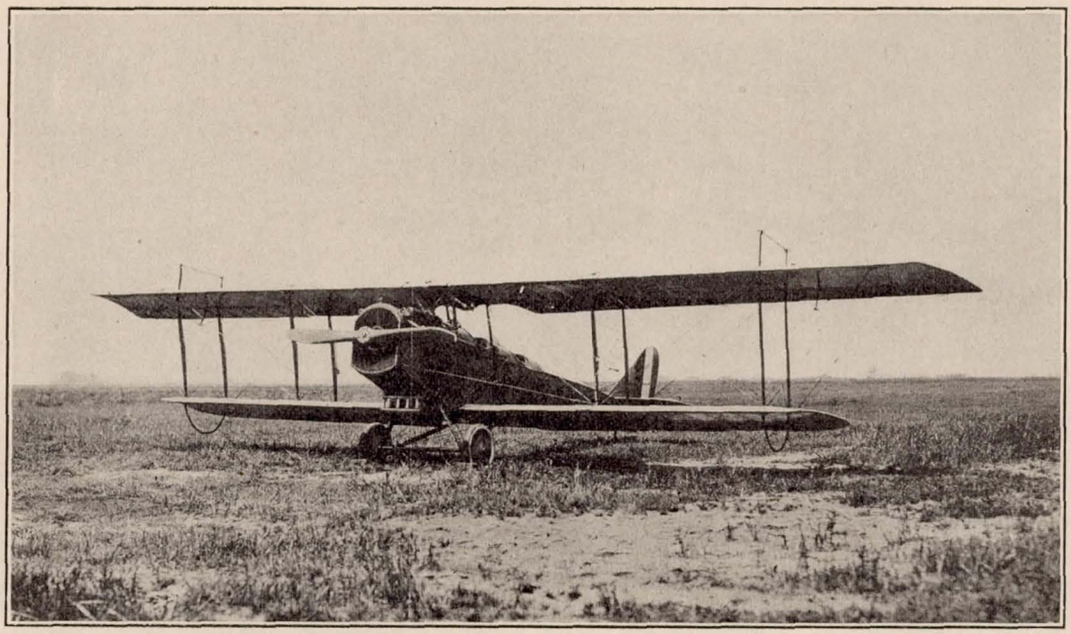




FIG. 1a

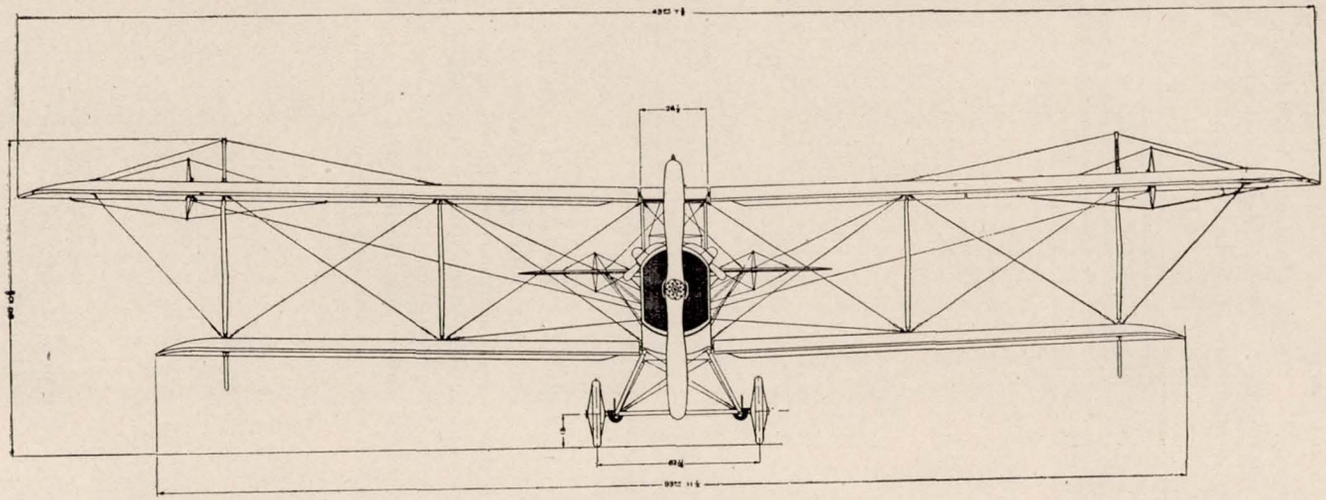


FIGURE 2 (b).

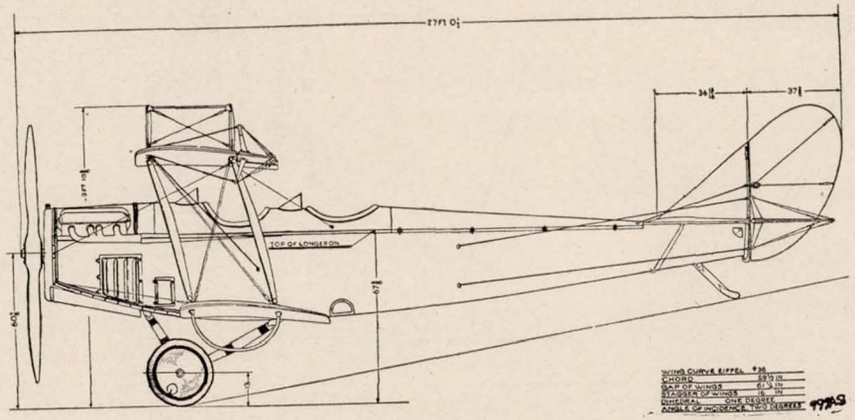


FIGURE 2 (c).

considerably less than it was supposed to be. The other propeller checked extremely well with the drawings, the mean blade angles for the two blades being correct within 0°.1 at all radii except within three inches of the tip, where the angle of setting was too large by 0°.35. The effect which this difference between the two propellers had on the results of the tests will be discussed elsewhere.

The most important factor from an aerodynamic standpoint is, of course, the type, form and arrangement of the main supporting surfaces. The wing section was accordingly checked up by direct measurement at several points on each machine, a frame being used which encircled the wing and provided base lines for measuring the cambers on both the upper and the lower

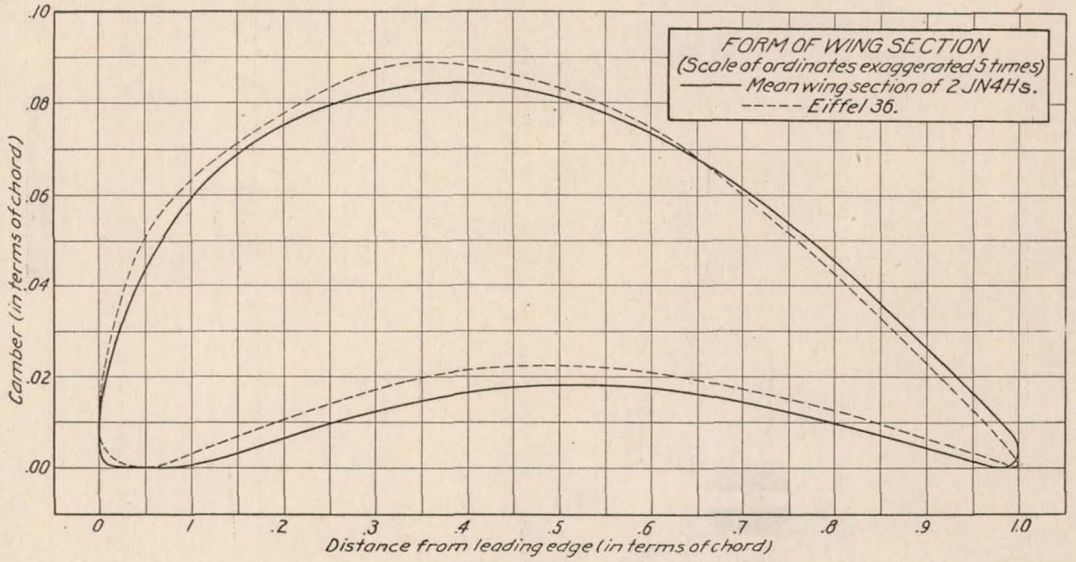


FIGURE 3.

surfaces. The section employed was nominally an Eiffel 36. Actually it varied from that curve by having a smaller camber on both surfaces. The maximum discrepancy between the Eiffel 36 and the mean wing section for the two machines was 0.006 of the chord, or approximately three-eighths inch, on the upper surface, and a very little less on the lower surface. The actual curve on the upper surface was considerably smoother than that of the Eiffel 36, the latter section having a rather abrupt change of curvature one-third of the way back from the leading edge. The mean section for the actual wings and the Eiffel 36 are plotted in figure

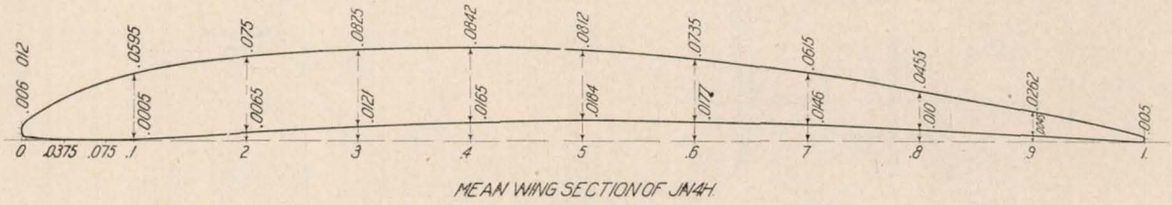


FIGURE 4.

3 with the ordinates very much exaggerated, such distortion of the plot making it easy to detect any unfairness of the curves or any difference between them. The true form of the section used is given in figure 4.

The difference between the mean sections for the two machines was negligible, being less than 0.002 of the chord at every point, and less than 0.001 at most points. Airplane No. 2 had a smaller camber than No. 1 on the whole upper surface and on the larger part of the lower

one. Although the differences happened to counterbalance each other so that the mean sections were nearly identical, the extreme divergencies between the cambers at corresponding points on the different wings were by no means negligible. For example, the ordinates for one lower wing on No. 2 were uniformly greater than those for the other lower wing on the same machine, the difference sometimes amounting to as much as 0.004 of the chord. It is improbable that wings can be manufactured by ordinary production methods with a greater uniformity of section than that found in these two machines, and, even if they could be made originally with greater accuracy, wooden ribs will not hold their curvature exactly when submitted to varying climatic conditions. Wind tunnel experiments indicate that the effect of changing the camber of an aerofoil by 0.004 of the chord is seldom serious, so long as the surface retains a smooth curvature, except in very thick sections such as are used in propeller blades and in internally braced airplanes such as the Fokker biplane and triplane. It appears to be fair to assume that the differences in section among the wings used on these machines will have no effect on their characteristics and that the mean section, as shown in figure 3, can be assumed to exist at all points.

The discrepancy between the actual form of the wing section and the curve on which it was supposed to be based points a dual lesson. In the first place, it draws attention to the need of making wind-tunnel models to represent the airplane as it is actually built, or to be built, not merely according to specifications which the shop may find itself quite unable to follow. It is of little use to construct model aerofoils accurate to within 0.002 inch if the full-sized wing which they represent departs by as much as three-eighths of an inch from the section which it is supposed to follow. Secondly, these measurements should serve to remind experimenters engaged in the design of wing sections of the futility of drawing forms which it is impossible to construct by ordinary methods. For instance, no airplane wing is constructed with the upper and lower surfaces running out until they intersect in a perfectly sharp trailing edge. Indeed, it is practically impossible to construct a model aerofoil for the wind tunnel with such a trailing edge, yet aerofoils are repeatedly drawn up in such forms. The result is that the model maker exercises his own judgment as to the extent to which the trailing edge should be rounded over, the airplane builder introduces a strip of wood or of steel tube for a trailing edge, and the drawing, the model, and the full-sized wing are likely ultimately to be of three quite different forms.

In the JN4H, the thrust line is parallel to the top longerons and the stabilizer, which is flat on its lower surface, lies directly on the longerons. A detailed discussion of the actual form and setting of the tail surfaces is of interest primarily in connection with the longitudinal balance of the machine, and it will be reserved for treatment in connection with that subject. The wings are nominally set at an angle of 2° to the top longerons, but the mean angle of incidence in both of the machines used in this work was somewhat greater than that, being 2°.25 in No. 1 and 2°.4 in No. 2. The variation of incidence along the wing, due to warping, to slightly imperfect rigging, and to the droop provided in the left wing to balance the propeller torque, was about 0°.3. The ailerons were rigged as nearly as possible to form a continuation of the upper wing, so that, when the stick was centered, the angles of incidence of the portions of the upper wing which carries the ailerons were very nearly the same as for the inner part of the wings. A small change in the rigging of the ailerons when in the neutral position has a marked effect on the lift and drag coefficients of the wings.

CALIBRATION OF INSTRUMENTS.

The first step in the making of any tests is necessarily a study of the accuracy and a determination of the calibration curves of the instruments employed. The standard instruments, used in all tests, are the altimeter, the tachometer, and the air-speed meter. The altimeter can readily be calibrated in the laboratory under a bell jar. Since the altimeter was used, in most of these experiments, only for determining the density correction, and since most of the work was carried out at less than 4,000 feet altitude, the permissible percentage error in altitude determina-

tion was quite large. An error of 130 feet in the altimeter reading, or more than 4 per cent at 3,000 feet, affects the density determination by only one-half per cent. The effect of such minor factors as the decrease of static pressure in the cockpit, due to the slip-stream velocity, can therefore be neglected. It is usually possible, at the time of calibrating the altimeter, to adjust the instrument so that the errors are negligible in such work as this at altitudes of less than 4,000 feet, and the scale readings can therefore be used directly without resort to a calibration curve.

The tachometers used were made by the Van Sicklen Co., and were of the chronometric type. No calibration of these instruments was adjudged necessary, as the readings of the instruments in the front and rear checked, and as a chronometric tachometer can generally be counted on to give readings very nearly correct so long as it gives any readings at all. If anything goes wrong the instrument usually stops recording entirely.

The calibration of the air-speed meters presents a much more serious problem than does that of either of the instruments just discussed, for several reasons. There are several possible sources of error in the air-speed determination. In the first place, the meter itself may be in error initially or may go wrong after some use. Errors of this type can be determined by calibration of the meter in a wind tunnel. In the second place, the pitot or venturi tube used for measuring the velocity head being located close to the machine and in air disturbed by the passage of the wings the velocity of the air past this tube is, in general, different from the velocity of the airplane relative to the undisturbed air. For example, the vortex theory of sustentation declares that there is, superposed on the rectilinear flow of air relative to the wing, a cyclic flow around the wing, so that the relative air speed above the wing is higher, and that below the wing lower, than the speed through undisturbed air. An air-speed meter having its head placed close above the wing would therefore give too high a reading, no matter how closely the instrument might have calibrated in the laboratory. Finally, the air-speed meter will not give a perfectly correct reading if the axis of the head is not parallel to the relative wind direction at that point. Inclination of the head to the relative wind results from the diversion of the air flow by interference, a diversion which extends to a considerable distance forward of the wings, and also from the changing attitude of an air-speed meter head fixed in the machine as the angle of attack is altered.

Since practically all free-flight testing requires the determination of the air speed from a meter the accuracy of that instrument is of great importance. In the determination of lift coefficients, for example, an error of one-half mile an hour in the measurement of the air speed at its mean value (about 65 miles per hour for the JN4H) has as bad an effect on the final result as would an error of 400 feet in the altitude determination. It is essential, therefore, that the instrument be calibrated in place on the airplane and that the calibration be repeated at intervals to guard against changes in the meter.

The air-speed meters used in these tests were Bristol instruments. They were graduated with a division at each mile, but the scale was uniform enough and open enough so that it was easy to estimate the reading to half a mile an hour. The heads were pitot-venturi tubes of the standard Army type, and were mounted on the left inner forward interplane strut, about 18 inches above the lower wing. The inner strut is preferable to the outer one because of the smaller length of tubing required to make connection to the meter and also because the flow of air at the inner strut is more nearly parallel to the plane of symmetry of the airplane, the relative air velocity at the outer strut having a considerable component parallel to the Y axis, which would cause the air to strike the tubes obliquely and so give false indications.

There are two classes of methods used for calibrating air-speed meters in position. The first, much used by the British, involves the use of a camera obscura for the determination of speed over the ground. The speed with which the image of the airplane crosses the field of view can be measured with great accuracy, but the ground speed for a given rate of travel of the image is directly proportional to the altitude, and the altitude must therefore be determined within one-half per cent or better, an accuracy beyond the reach of any altimeter. The altitude can best be determined by the use of a second camera obscura or of a theodolite in conjunction

with one camera obscura, the vertical angles of the plane as seen from two different points at the instant when it crosses a line connecting those two points giving the necessary data for computing the altitude. The effect of the wind can be determined and corrected for either by measuring the velocity of a puff of smoke fired from the airplane or by flying across the field of view in three different directions, one after the other, and measuring the ground speed in each direction. There is only one camera obscura at Langley Field, and it was not deemed advisable to secure another. The camera obscura therefore has not been used for calibrating the air-speed meters in these tests.

The second method, and the one so far used in the work of the National Advisory Committee, is simpler and more direct, requiring only the timing of the airplane over a measured course. The course laid off at Langley Field is 5,600 feet long, and two horizontal wires, one directly above the other and about 3 feet apart, are carried on poles at each end. One of these observing stations is shown in figure 5. The airplane was flown over the course at an altitude of from 200 to 1,000 feet, the higher altitudes generally being used at the lower speeds, where there was some danger of stalling or side slipping or starting a spin. The pilot kept the speed as nearly constant as possible and the observer recorded the air-speed meter reading every 5 seconds. Two or three runs were made in each direction at each speed, the speeds at which the meter was calibrated being spaced about 5 miles per hour from the maximum down to the minimum. The ground speed of each run is determined by observers at the ends of the course, the two stations being in telephonic communication. The effect of the wind is eliminated, assuming that its direction and velocity do not change between runs, by computing the mean air speed for successive runs made approximately at the same speed and plotting it against the mean ground speed for the same runs. This method is much more satisfactory, when the pilot is skillful enough to make his runs at air speeds very nearly uniform and close to the desired speeds, than any attempt to measure the component of wind velocity along the course and correct each run for the effect of that component, as both direction and velocity of the wind are so subject to change with altitude that measurements within 50 feet of the ground give little information as to the conditions existing at three or four hundred feet. If the wind is blowing across the speed course, or at an angle to it, the machine should be kept pointed along the course and allowed to drift rather than being headed into the wind in such a way that the path over the ground will be parallel to the course. The right and wrong methods are shown in figures 6a and 6b, where W is the vector representing wind velocity, A the air speed, and G the resultant speed over the ground. In figure 6b the air speed is greater than the component of ground speed parallel to the course, in whichever direction flown, and the timing over the ground of a machine flown in this manner would therefore give too low a mean true speed. In figure 6a, on the other hand, the two quantities just mentioned are exactly equal.

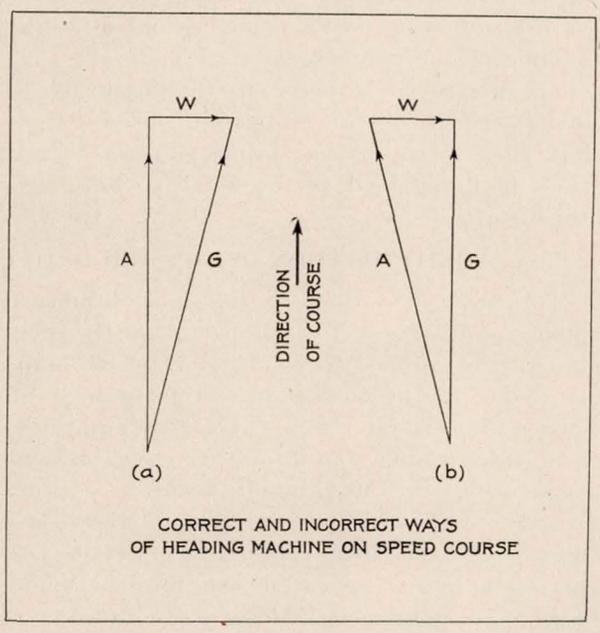


FIGURE 6.

The calibration curves found in this way for the meters in the rear cockpits of the two machines are plotted in figure 7. It will be observed that they follow the same general form, the relative displacement between the two curves probably being due to an error in one of the instruments. It might be expected that the meter would read low at very low speeds and large angles of attack, due to the inclination of the head to the relative wind, but it actually appears to read high. This result has been obtained in tests on both airplanes, and there is

little doubt of its accuracy, although the error in calibration at low speeds is greater than that at high, both because the effect of wind variations is more marked at low speeds and because it is difficult for the pilot to hold a straight course over the ground while flying at large angles of attack. In figure 8 the corrections to be applied to the air-speed meter reading are plotted against indicated speed, these curves serving to give a clearer idea of the extent of the errors involved in the direct application of uncorrected meter readings than do those of figure 7.

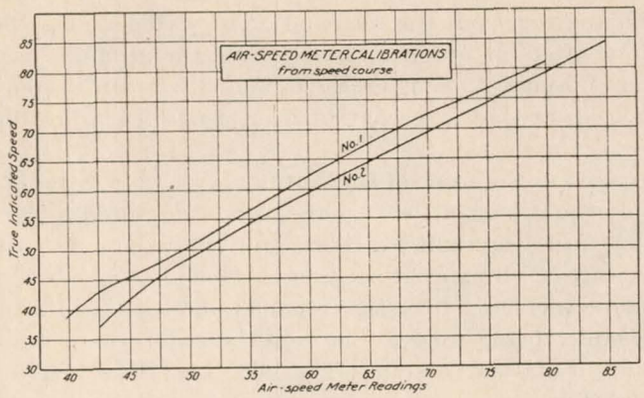


FIGURE 7.

When tests are made at high altitudes, where the difference between the indicated and true air speeds is large, the meter calibration correction should be applied to the indicated speed first, and the result thus obtained should be multiplied by the density correction to give the true speed. This order of procedure is necessary because the flow of air about the wings, and therefore the interference effect on the instrument readings, depends on the indicated, not the true, air speed. The meter calibration curve varies somewhat with changes in the loading of the machine, as such changes alter the relation between the angle of attack and the indicated speed, but the effect of any ordinary variations in flying load is too small to be taken into account.

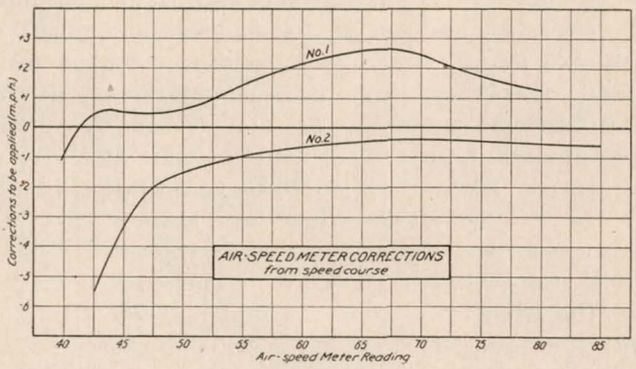


FIGURE 8.

DETERMINATION OF LIFT AND DRAG COEFFICIENTS: METHODS EMPLOYED.

It is very desirable that data be obtained on the lift and drag in free flight of full-sized airplanes and parts thereof, in order that the designer may gain some knowledge as to the corrections to be applied to wind-tunnel results and as to the extent to which those results can be trusted. The problem is an extremely difficult one for many reasons, some of which will be discussed in detail later on in this report, and the work which has so far been done leaves much that is uncertain and many questions the solution of which can not even be attempted until new types of instruments and more accurate experimental methods have been devised.

There are three methods which have been suggested and employed to some extent for finding the lift in flight. The first two permit of the determination of the lift of separate parts (in particular, the wings), while the third, the simplest, and the only one which has been used in the work done at Langley Field, gives only the lift coefficients for the airplane as a whole. The first and most obvious of these methods proposes the measurement of the lift of any part by the interposition of weighing devices between that part and the remainder of the airplane. For example, the wing hinges might be attached to the body through the medium of springs. There has been a great deal of discussion of the possibilities of this method, but the mechanical difficulties are considerable, and not much actual work has been done. The second method depends on the measurement of the pressure at a large number of points on the surface of the wings (and, if desired, on the tail of the body) and the determination of the total lift by the integration of these pressures over the whole surface. This has been used to some extent in England, and similar work is planned for Langley Field during the coming year. The pressures can be measured, once the apparatus is satisfactorily constructed, with great ease and accu-

racy, and the only errors to which the method is subject are those inherent in all free-flight measurements.

The third method is, as was just noted, the simplest, in that it requires the least special apparatus. In the equation $L=L_c\times\frac{\rho}{g}\times V^2$ it is known that L is equal to the weight of the machine when the flight path is horizontal, and that it departs only very slightly from that figure for any ordinary inclination of the path (short of a steep dive). Since ρ can be computed from measurements of the pressure and temperature, the determination of L_c requires only the measurement of V. As a matter of fact, since the air-speed meter records not the true speed but the product of $V\times\sqrt{\rho/\rho_o}$, the term ρ/g can be eliminated by the substitution of indicated for true air speed, and the equation above can be written:

$$L=L_cCV_i^2$$

Where C is a correction constant taking into account the gravity constant g and the conversion factor changing V_i from miles per hours to feet per second. Although a small part of the lift is due to the body and the tail surfaces have a substantial effect at some angles, it is convenient to divide the lift by the wing area and write the above equation in the form

$$L=L_cCAV_i^2$$

With a good meter and careful calibration the air speed can certainly be determined with an error of less than 1 mile per hour and probably less than $\frac{1}{2}$ mile per hour, and the lift coefficient at any given instant during a flight can therefore be computed very accurately. In substituting for L in the characteristic equation, allowance has to be made for the progressive diminution of weight by the comsumption of fuel and for the direct balancing of part of the weight of the machine by the vertical component of the propeller thrust.

Since the lift coefficient is a function of angle of attack, it is of very little use to compute the value of the coefficient at any instant during a flight unless this angle at the same instant is known, and it is in the determination of this angle that the greatest difficulties arise. The conventional type of "incidence indicator," embodying a pivoted vane and two Pitot tubes at a considerable angle to each other or a sphere pierced with two holes, is useless unless some other means is employed to calibrate it in position, as the instrument has to be placed in air disturbed by the passage of the airplane, and the motion of the instrument relative to this disturbed air, as already noted in connection with the calibration of the air-speed meters, may be of quite a different nature from its motion relative to the air at a great distance. The disturbance of the airby the wings extends to so great a distance (three or four chord lengths) in front of the leading edge that it is impracticable to carry the incidence indicator far enough forward entirely to escape this disturbance.

Since the angle of attack is the inclination of the wings to the relative wind, it is equal to the difference between the inclination of the wings to any fixed reference plane and the inclination of the relative wind to the same plane. In particular, the angle of attack can be determined if instruments are available which will give the angles between any line fixed in the airplane and the horizontal and between the relative wind and the horizontal. The first of the these angles is given, provided that the machine is in steady rectilinear flight, by a liquid longitudinal inclinometer. The second can not readily be determined directly, but the inclination of the flight path to the horizontal is given by a rate-of-climb meter in conjunction with an air-speed meter, and this is equivalent to the inclination of the relative wind if the movement of the air is exactly horizontal. In the particular case where the flight path is level the rate-of-climb meter can be replaced by a statoscope. The largest error in the determination of angle of attack by this method arises from the assumption that the air moves only horizontally. An ascending current having a velocity of only 1 foot per second changes the angle of attack, for a given attitude of the machine relative to the earth, by nearly 0°.7 at an air speed of 60 miles per hour. This is a very gentle ascending current, and it will be shown later that vertical currents which have actually been encountered during these experiments have affected the apparent angle of attack by more than 1°.

The statoscope used is shown in figure 9. The tube was kept separate from the vacuum flask, instead of mounting both in one case as is customary, in order that the flask might be

placed behind the instrument board and the space occupied on the board be kept down to a minimum. The use of the statoscope makes it practicable to keep the mean rate of climb or descent down to 20 feet per minute except at very large angles of attack, and a rate of climb of 20 feet per minute affects the angle of attack at 60 miles per hour by less than 0°.25.

The ordinary commercial type of longitudinal inclinometer proved unsatisfactory, first, because the scale was not open enough to permit the angles to be read as closely as was desired, and, second, because the face of the instrument was perpendicular to the instrument board. The observer's eye being well above the board, the observer looked down on top of the meniscus and across it at the scale behind, and the parallax error was large. An instrument was designed to obviate these difficulties, and is shown assembled in figure 10. Figure 11 illustrates the tube removed from the case. The front tube and scale make an angle of 20° with the surface which rests against the instrument board. The mean distance between the two surfaces of the column of liquid is 8 inches. The scale is divided in degrees, the divisions being roughly one-eighth inch apart, and it is easy to estimate to 0°.1. The liquid is a mixture of glycerin and alcohol, colored with red ink. The damping of oscillations depends on the viscosity of the liquid, and this can be controlled by varying the proportions of alcohol and glycerin. The tube is constricted at one point to increase the damping. Parallax was avoided by mounting a mirror beside the instrument, the observer bringing the reflection of his eye in line with the meniscus.

It unfortunately has not been possible to base the measurements of the drag entirely on data obtained in flight, as no satisfactory means of measuring the propeller thrust is available as yet. It is therefore necessary to rely on a wind tunnel test for the propeller characteristics. A partial check can be obtained on the wind tunnel results by measuring the slip-stream velocity, as described in another section of the report. Knowing the revolutions per minute and the true air-speed, the value of $\frac{V}{ND}$, the propeller slip function, can be computed, and the thrust can then be determined from a curve of T_c against $\frac{V}{ND}$. The equation for thrust is:

$$T = T_c \times \rho/g \times V^2 \times D^2$$

Since, as in the case of the lift $\frac{\rho V^2}{\rho_o}$ is equal to V_i^2, this may be written:

$$T = T_c \times C \times V_i^2$$

where C is a constant including correction factors for units and D^2, which is constant for a given propeller. A model of the propellers used has been tested at the Leland Stanford Jr. wind tunnel, and the curves of T_c and efficiency are reproduced in figure 12. Plotting the thrust against the angle of attack, and dividing the total lift by the horizontal component of thrust, a curve of L/D can be obtained.

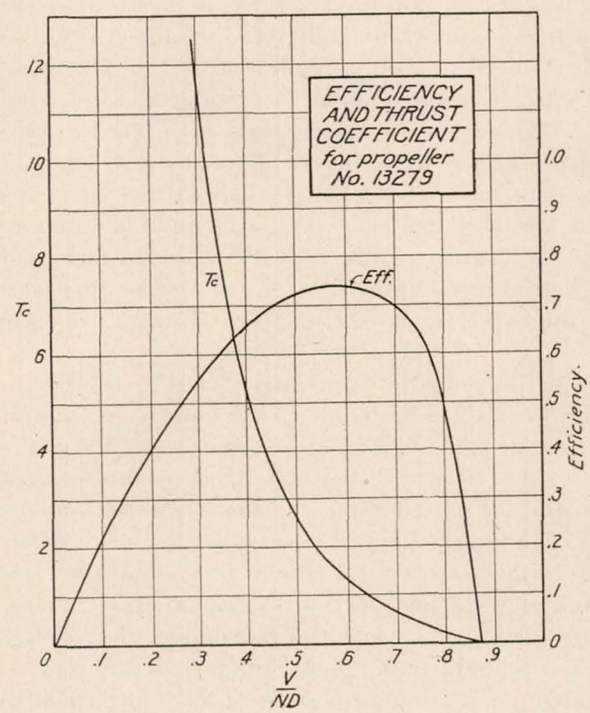


FIGURE 12.

Serious as are the errors which ascending and descending currents produce in the lift curve, they are trifling compared with those which appear in the thrust computations, due to the same cause. An inclination of the relative wind has the effect of rotating through a corresponding angle the axes of lift and drag, so that the drag of the airplane is opposed not only by the thrust but also by a component of the weight. An ascending current having a velocity of 1 foot per second diminished the thrust required for level flight by 9 per cent if the L/D for the complete airplane is 8 and the machine is flying at 60 miles per hour. The error is directly proportional to

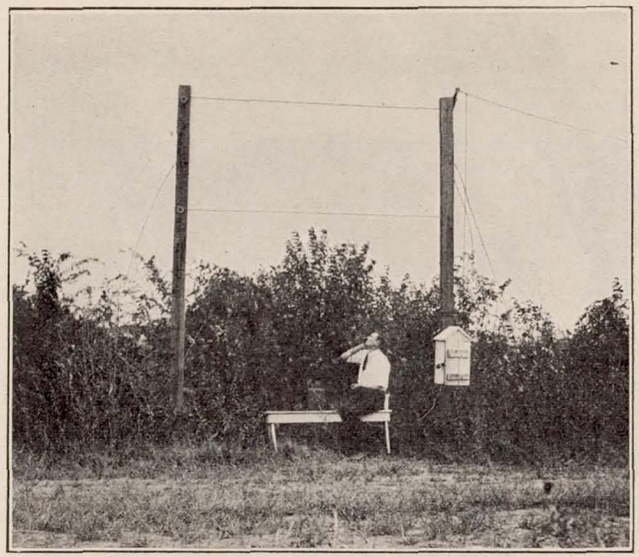


FIG. 5.—SPEED COURSE OBSERVATION STATION.

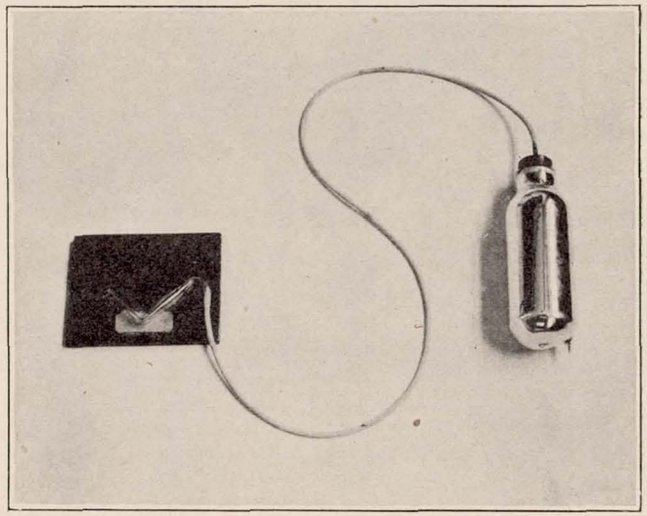


FIG. 9.—STATOSCOPE.

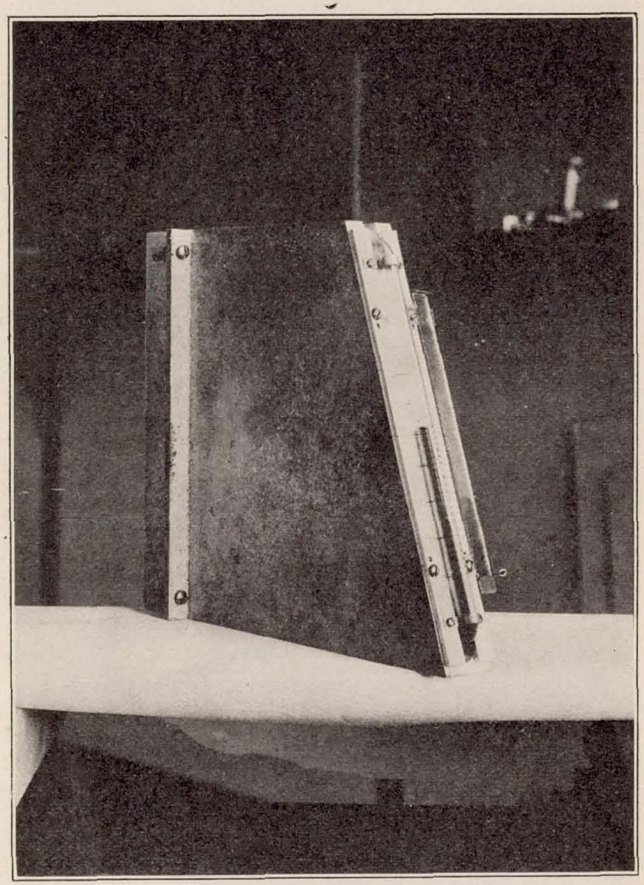


FIG. 10.—INCLINOMETER.

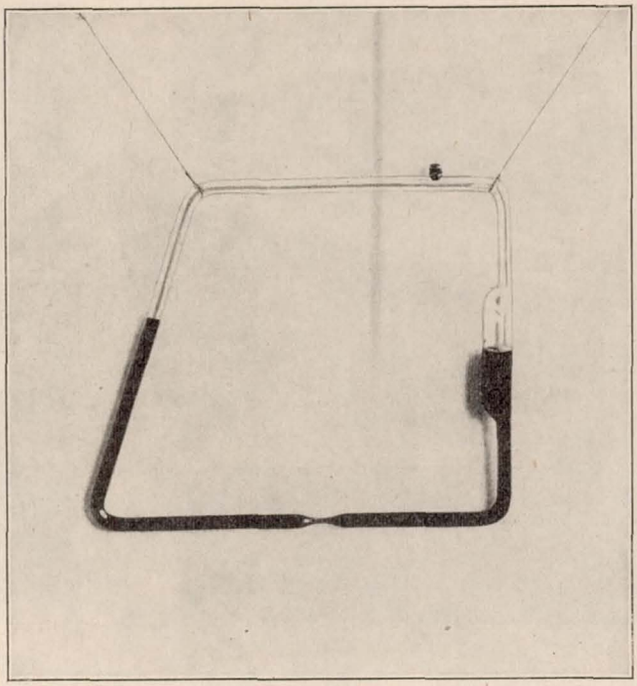


FIG. 11.—INCLINOMETER TUBE.

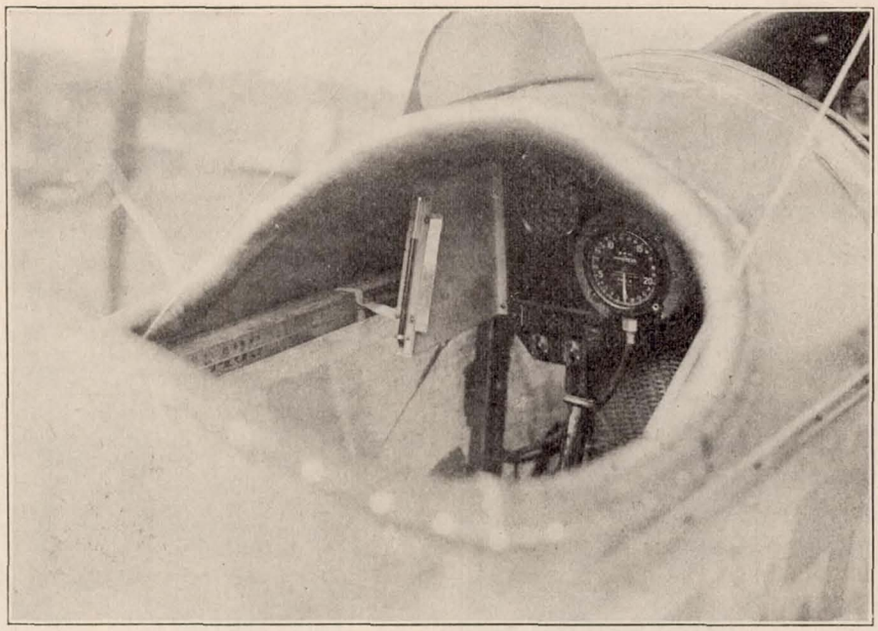


FIG. 13.—COCKPIT AND INSTRUMENT BOARD OF NO. 1.

the velocity of the vertical current and to the L/D ratio, inversely proportional to the speed of flight. If the rising current had a vertical velocity of 11 feet per second, the air speed and L/D being the same as before, no thrust would be required and the machine would soar without engine power. Such currents as this seldom if ever exist, but rising and falling currents of smaller velocities are almost omnipresent. They account for many seemingly wild results in this and other similar work, and the only way to eliminate their effects is to run a great number of tests of the same sort, under all light and weather conditions and over as many different types of terrain as possible, and then average the results.

Figure 13 shows the instrument board in the observer's cockpit of No. 1, with inclinometer, air-speed meter, altimeter, and tachometer installed. The altimeter does not appear in this photograph, being hidden behind the cowling at the right. The arrangement in No. 2 is practically the same.

The tests were carried out at altitudes varying from 1,500 to 4,000 feet. It was not considered safe, in view of the danger of falling into a spin when flying at large angles and of the possibility of a forced landing, to work below the former altitude. The altitude chosen on any particular day depends chiefly on air conditions, the climb being continued far enough to escape the "bumps" frequently found near the ground. Each "run" continued for from 1 to 2 minutes, the pilot being instructed to fly level (using the statoscope to detect changes in altitude) and at a constant air speed during that period. The observer read and recorded the readings of the air-speed meter, the inclinometer and the tachometer every 10 seconds, and noted the altimeter reading and the air temperature at the beginning of each run. The pilot's task was a very difficult one, for he had constantly to watch the statoscope and air-speed meter, in addition to holding the machine steady laterally and watching out for other airplanes. Besides all this, when flying over the speed course to calibrate the meter the pilot had to steer a straight course over the ground between the two observing stations. Test flying is a very highly specialized branch of work, the difficulties of which are not generally appreciated, and there is no type of flying in which a difference between the abilities of pilots thoroughly competent in ordinary flying becomes more quickly apparent. Most of the piloting for the committee has been done by Mr. E. T. Allen and Lieut. H. M. Cronk, but seven other pilots have been used on one or more occasions.

In order to determine the minimum speed in steady flight and to secure data for comparison with wind tunnel tests over the whole range of angles customarily covered by the latter, it was necessary to fly horizontally at an angle at least equal to the angle of maximum lift and as much larger as possible. The procedure in attaining these high angles was to throttle the engine to the lowest speed at which level flight could be maintained, and then open the throttle gradually, drawing the stick back at the same time. The airplane can thus be flown level in a very badly stalled condition, the action of the longitudinal controls being reversed (i. e., if the machine is losing altitude it is necessary to decrease the angle of attack, pushing the stick forward, in order to ascend). Furthermore, the airplane is very unstable laterally at angles in excess of 12° or 13°, and it is prone to fall off into side slips. Most pilots, in trying to fly at extremely high angles for the first time, are unable to keep the machine in equilibrium for more than a few seconds. One of the pilots flying for the committee, after considerable practice, became very skillful in this work and found it possible, given favorable weather conditions, to maintain steady level flight for an indefinite period with the throttle wide open and the machine stalled to an angle of attack of 18° or a little more. The ailerons alone are very ineffective in maintaining lateral stability at large angles, as any raising of one aileron greatly diminishes the drag on that portion of the wing, while drawing down the other aileron correspondingly increases the drag there. The result is that a large yawing moment, nearly if not quite sufficient to overcome the effect of the rolling moment due to the ailerons, is produced and tends to force the machine into a spin. It is necessary constantly to use the rudder in conjunction with the ailerons to a considerably larger extent than is necessary at normal angles.

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RESULTS OF THE TESTS FOR LIFT COEFFICENTS.

A number of tests (about 10) were made on each airplane. Some of these have not been plotted up or included in the averages, either because they were not extended over a large enough range of angles or because they contained results which were self-contradictory or because it was found, when an attempt was made to work them up, that essential data were lacking. In selecting tests to be incorporated in the final tabulation no attempt was made to pick those which would check well with each other, and the results were not even compared until the final choice had been made and the computations completed. In order to indicate the degree of consistency obtained among the various factors on successive observations in one typical flight, the angle of attack, as determined by the inclinometer, is plotted against the indicated air speed in figure 14. As already noted, observations on the two instruments were taken every 10 seconds, and each pair of readings is plotted as a separate point. Where two or more readings corresponded to exactly the same point the fact is indicated by the proper number of concentric circles. There are about 50 points represented in figure 14, yet there are only two or three which depart from a smooth curve by more than one-half degree.

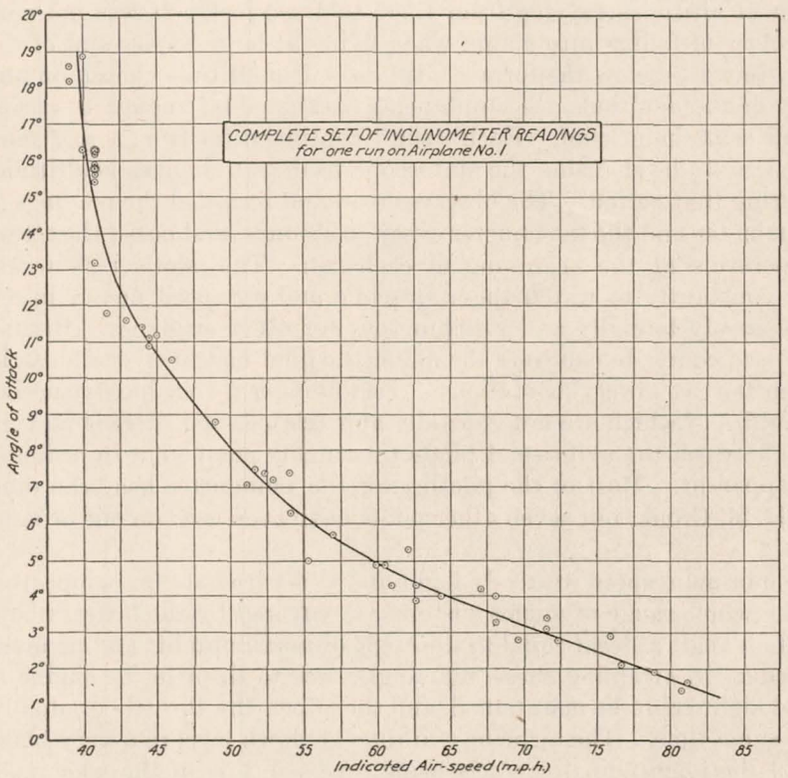


FIGURE 14.

Figure 15 gives the curve of L_c against angle for No. 2, with all the points computed from four tests marked. At angles of attack up to 10° the agreement among the four curves is fully as good as would be expected for a like number of wind-tunnel tests on the same model. Beyond that angle they begin to diverge, but three of the four sets of points stay close together throughout. The very large discrepancy between these three and the fourth at large angles may be explained by the failure of the pilot in the July 30 test to hold the path level. In seeking to fly at the lowest possible speed, he probably allowed the machine to settle or "pancake," so that the true lift was less than the weight of the airplane.

The mean lift curves for No. 1 and No. 2 are brought together in figure 16. The difference between the two is unfortunately not so small as that between the curves for the various tests on a single machine, and the reason for the discrepancy is not apparent. The difference between the two machines certainly is not great enough to account for it, although the reserve tank in the upper wing of No. 1 might affect the lift by a small amount. However, even if the difference between the two lift curves be regarded as wholly due to error in the experiments, the two are nearly enough alike to indicate the general form of the curve and to permit of interesting deductions.

The most important result that can be drawn from such work as this relates to the comparison between free-flight and wind-tunnel results. It has not been possible as yet to have an accurate model of the JN4H made up for wind-tunnel test, but a great deal of work has been done on the JN2[1], and this can be used as a basis of comparison. The JN2 has an Eiffel 36 wing-section, like the JN4H, but it differs from the latter in that its wings are of equal span and in a number of other details. The JN2 has a larger down load on the tail than has the 4H, as will be shown in connection with the discussion of balance, and the actual lift of the wings must therefore be greater. It would then be expected, other things being equal, that the lift coefficients here computed, which ignore the tail load entirely, would be a little smaller for the 2 than for the 4H, but the difference would hardly exceed 3 per cent.

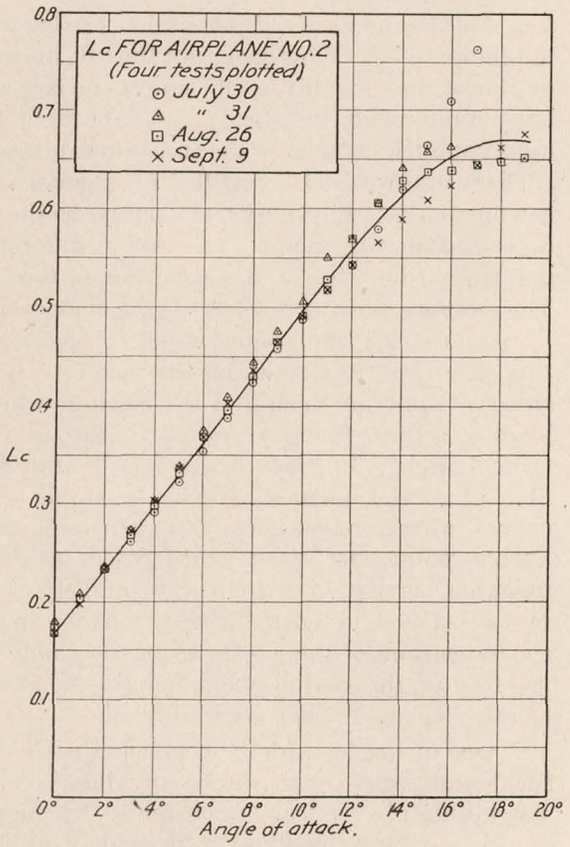


FIGURE 15.

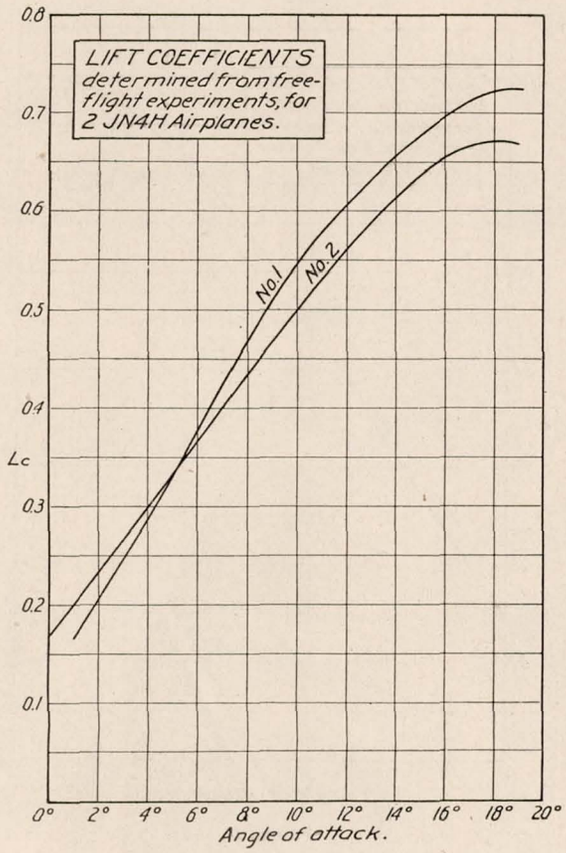


FIGURE 16.

The lift coefficient for the JN2 model and the mean coefficient for the two full-sized machines are given in figure 17. The coefficients for the model, like those for the full-sized machine, are based on the lift of the whole airplane and not on that of the wings alone. The two curves run fairly close together up to 6°, although the lift of the model is distinctly the larger, even when allowance is made for the effect of the difference in tail load just mentioned. The model lift coefficient at angles below 6° is larger than that given by the free-flight tests for either No. 1 or No. 2. At angles in excess of 6° the model lift coefficient begins to drop off rapidly by comparison with the free-flight values. The burble point for the former comes at an angle nearly 4° smaller than that for the latter, and its maximum lift is about 15 per cent less, so that the minimum speed, or, as it is usually called, landing speed, computed from the model test, would be three miles an hour higher than that found by experiment. Actually, however, the model test gives the practicable land-

[1] Third Annual Report, National Advisory Committee for Aeronautics, p. 278 et seq.

ing speed more closely than does the free-flight test, for the customary angle of attack in a good landing is about 12°, an angle at which the lift coefficient is almost exactly equal to the maximum lift coefficient of the model. In order to land the machines which were the subject of these tests at the lowest speed at which they can be flown, the tail skid would have to touch the ground while the wheels were still 16 inches above its surface (assuming the downward slope of the flight path at the instant of making contact to be 2°). As every pilot will recognize, a landing in such an attitude would be distinctly unusual, to say the least. As has already been pointed out, it requires exceptional skill to fly at angles of 15° or more, and it would not be safe for any pilot to attempt it near the ground. It is, therefore, evident that the burble point is of very little practical interest in airplane design, as it is improbable that any pilot ever flies his machine at that angle voluntarily except for a very brief interval in the course of a stunt or when testing for minimum speed. Whether or not the rule hinted at above, that the lift coefficient at the largest angle practicable for steady and safe flight is approximately equal to the maximum lift coefficient of the model is justified for general use can only be determined by tests, similar to those described in this report, on many different machines using wing sections of different forms. The methods now used seem to give a good approximation to the landing speed, at least in this case, but it should be distinctly understood in applying them that the machine when landing is not flying at or very near to its critical angle. In view of this fact, it is probable that the menace of an "unstable lift curve" which breaks sharply after passing the burble point, has been exaggerated, as the unstable portion of the curve is unlikely ever to be reached in normal flight, judging from the indications of these tests as to the changed position of the burble point and the behavior of the airplane in that neighborhood.

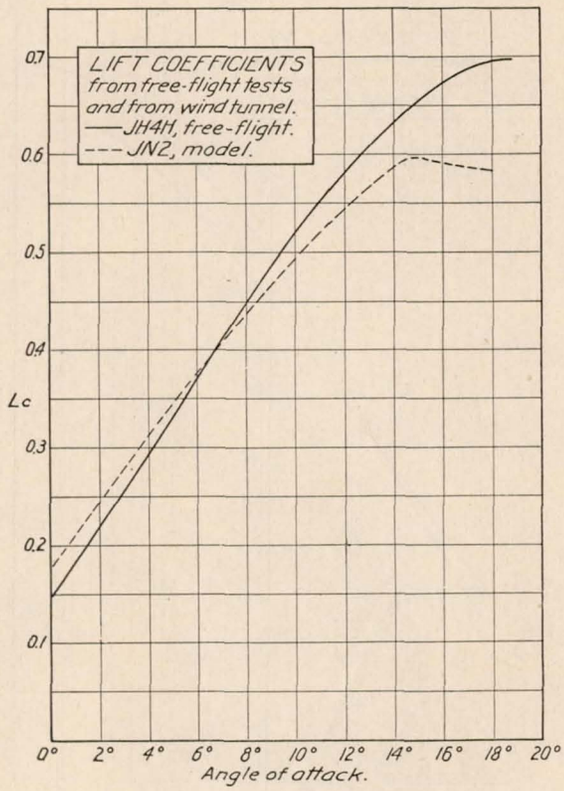


FIGURE 17.

One of the tests for lift coefficient on No. 2 incidentally gave some interesting data on the magnitude of vertical air currents. Some of the runs during this flight were made over the water (Hampton Roads) at a maximum distance of about a mile from the land and others, at nearly the same speeds, over the land. When the results were worked up it was found that the runs over the water and those over the land gave two distinct sets of curves, and that the angle of attack for a speed of 78 miles per hour was greater by 1° on the first set than on the second. This leads to the conclusion that the air was descending over the water or ascending over the land or both, and that the vertical velocity of the air in one place relative to that in the other was 120 feet per minute. This is undoubtedly an exceptional condition, as subsequent tests, although they frequently showed a difference in angle with the kind of country over which the machine was passing, indicated no other vertical velocities as large as that just mentioned. It should be noted that the flight just described took place in the morning, on a sunny day, and that all the observations were taken at a height of 2,700 feet. Since the results obtained on the runs over the land checked well with the other tests on the same machine it is probable that the vertical velocity there was not very large, and that most of the relative movement deduced was due to a downward motion of air over the bay, or at least over that portion of it covered by the flight.

A much disputed question relates to the effect of the slip-stream on the lift of an airplane. Although no attempt at quantitative measurements in inclined flight has as yet been made, the minimum speed attainable has been observed under various conditions of engine operation, and no indication of a marked slip-stream effect on lift has been apparent. Some such effect probably exists, but it is certainly small. The minimum speed with throttle wide open is, to be sure, somewhat less than the minimum speed in gliding, but the difference is not too large to be accounted for by the lesser total lift in the first case, due to the vertical component of the thrust-balancing part of the weight of the machine directly.

RESULTS OF THE TESTS FOR DRAG COEFFICIENTS.

In working up the results of the tests for drag the procedure followed was in general analogous to that just described for lift. The primary curve, corresponding to the plot of inclinometer readings against speed, was one of $\frac{V}{ND}$ against angle or speed (usually the latter). Such a curve for a single flight is given in figure 18, each point representing a single pair of readings (of air-speed meter and tachometer). It will be noted that the points do not lie on the curve with any such exactness as do those in figure 14, and that they separate into little groups. Each group of points includes the readings taken during a run in a straight line and at an approximately constant speed, and each group defines a little curve of its own, the slopes of these short subsidiary curves being considerably greater than that of the mean curve connecting them. This apparent discrepancy is due to the inertia of the airplane, which causes it to delay appreciably in responding to changes of condition. For example, if the engine speed drops slightly from any cause, there is a distinct interval before steady conditions are restored by a decrease in air speed and an increase in angle of attack, and if the engine speed returns to its original value after a few seconds the air speed will hardly have changed perceptibly in the meantime. If, on the other hand, the air speed changes, the engine speed responds almost instantly. If, for example, the air speed increases, the angle of attack of the propeller blades against the air falls off, the resisting torque of the propeller decreases, and there is an unbalanced torque tending to speed up the rate of rotation. Since the moment of inertia of the rotating parts is small, the response to this accelerating torque is, as already noted, very rapid. The result is that N can make considerable momentary changes, producing a corresponding effect in $\frac{V}{ND}$, without appreciably affecting V, but that any change in V is promptly followed by the corresponding change in N, and the points obtained during a short run with the conditions nearly but not quite constant therefore plot as a line nearly parallel to the axis of $\frac{V}{ND}$.

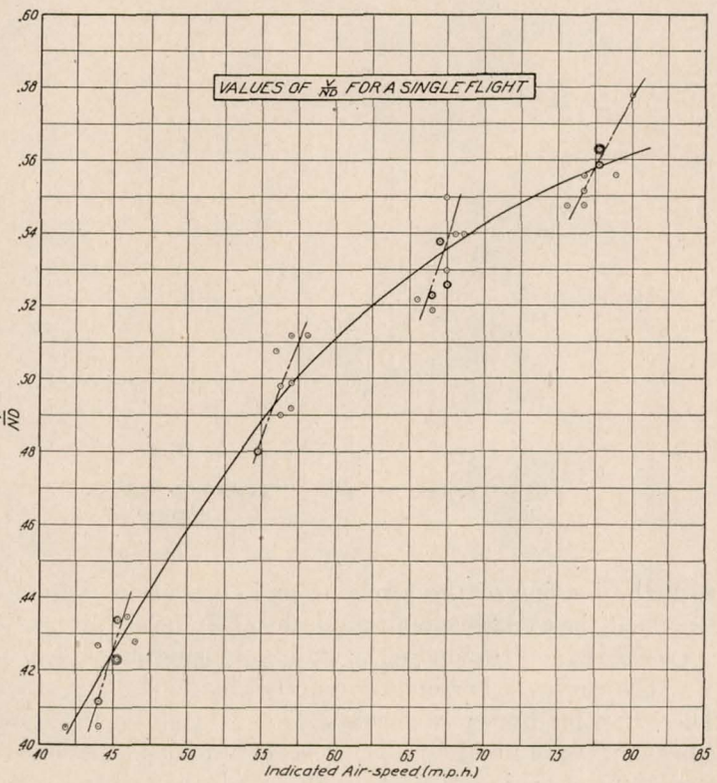


FIGURE 18.

The difference between successive tests was, as would be expected, greater than in the case of the lift coefficient, both because of the very large effect of vertical currents and because of the failure of the pilots in some cases to keep the path level. The extreme results for a given angle, however, seldom varied by more than 10 per cent. The errors in the determination are much greater at very large and at very small angles than at those in the neighborhood of the maximum L/D, partly because there were few tests which extended to very large angles. Even those tests which covered the full range of angles spread out widely at the ends of the curves, although very closely bunched in the intermediate portion. There was, as will be seen a little later, a marked difference between the results for the two machines, exceeding 10 per cent for a considerable range of angles. This difference can be attributed largely to the difference in the propellers, a difference already noted in the first part of the report, and it is probable that, since the propeller used on No. 2 was the more warped, the results given for the drag and L/D on No. 1 are more accurate than are those for No. 2. A test was made with the propellers interchanged, and the results obtained from No. 2 on that occasion checked very well with the mean curve for No. 1.

The mean curves of thrust for the two machines are given in figure 19. These curves call for no special comment, their general form being evident. The thrust for a given angle varies

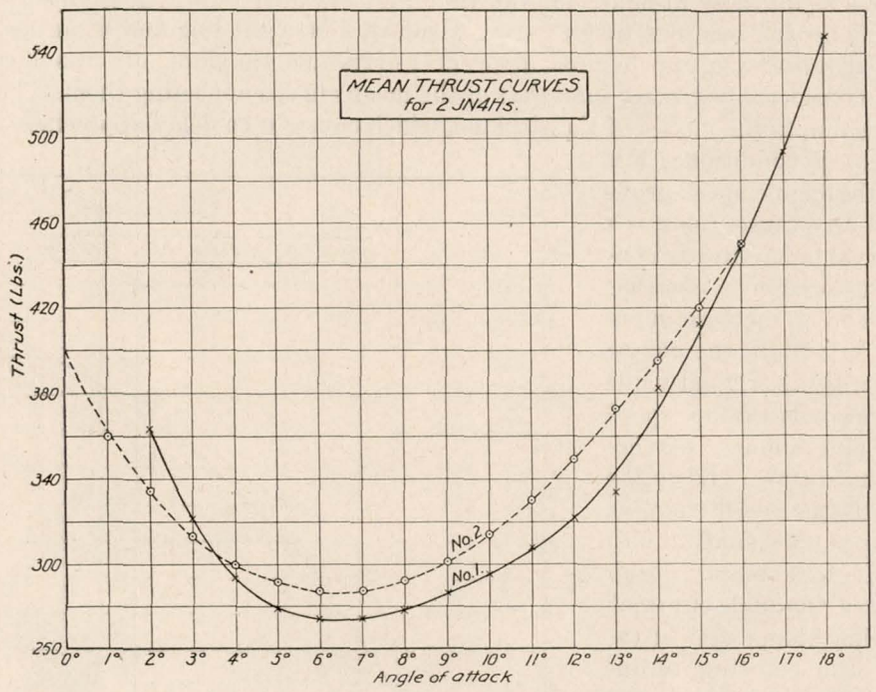


FIGURE 19.

with the loading of the airplane, and the curves therefore are somewhat indefinite, but they represent the average condition in the JN in level flight satisfactorily. The thrust given in these curves is that corresponding to standard atmospheric density.

The curves of horsepower required for level flight at standard density are given in figure 20. The curve for horsepower available is plotted on the same sheet, its form being based on the efficiency curve for the propeller, as determined at Leland Stanford Junior, and on the computed variations of engine speed with air speed, the throttle remaining wide open at all times and the engine torque being assumed constant. In order to make the intersection of the curves check with the maximum speed as determined by test it was necessary to take the engine horsepower as 130 (a value which appears reasonable, as the engines had seen a considerable amount of service and would not turn up beyond 1,530 revolutions per minute in level flight with the propeller normally used on No. 1, or 1,570 revolutions per minute with that used on No. 2). It will be noted that the curves of horsepower available and required have their second intersection at an angle a little smaller than the burble point. This checks very well with the observed fact that,

with the throttle wide open and the machine flying level, it was not quite possible to reach the burble point. This is shown by the mean lift curves, which stop just short of the critical angle. This coincidence of computed and observed results at the lower end of the horsepower curve affords additional reason for confidence in the validity of the method employed for using wind-tunnel data on the propeller in conjunction with measurements on the complete airplane in free flight.

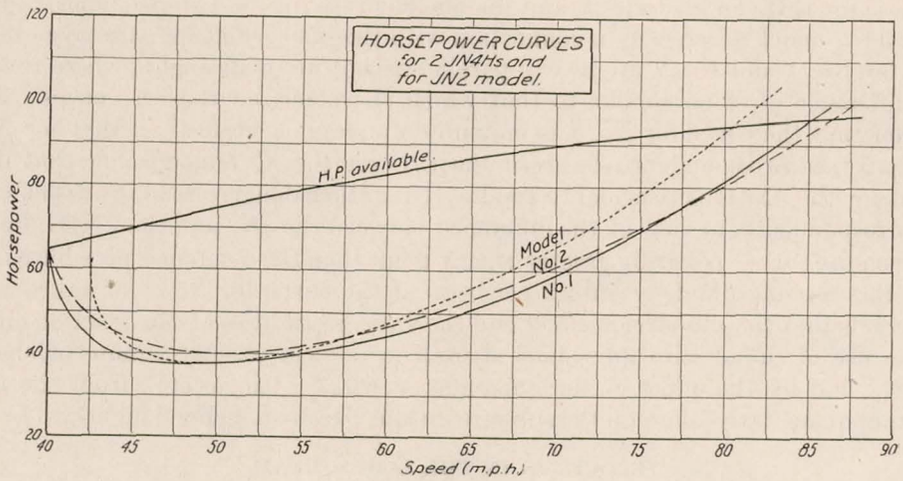
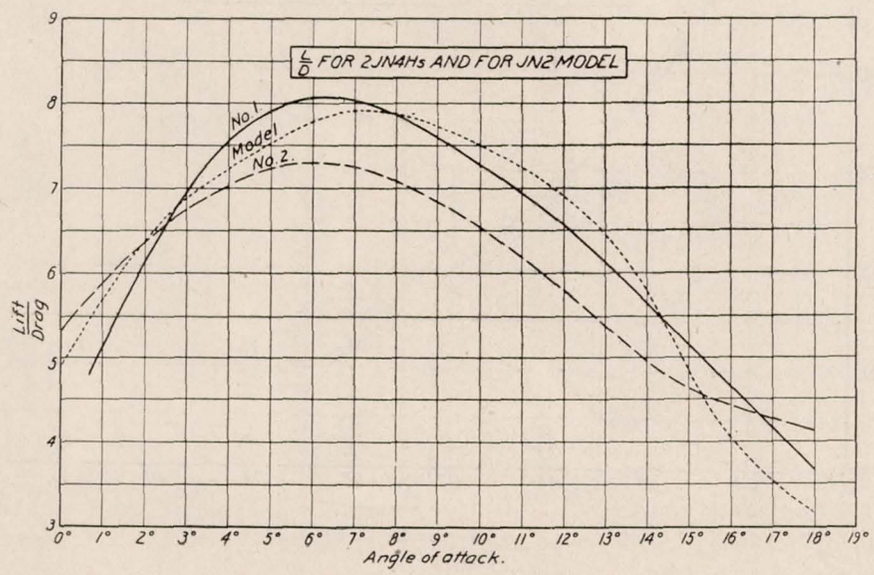


FIGURE 20.

The air speed for best climb is deduced from the horsepower curves to be 56 miles per hour. No thorough tests on climb have been made, but the air speeds adopted by the pilots who have flown these machines, when they desired a maximum rate of ascent, have ranged from 48 to 57 miles per hour, with the most skillful and experienced pilots, in most cases, choosing a speed nearer to 48 than to to 57. It appears, then, that the air speed which would be recommended as a result of the study of the curves of figure 20 is very nearly correct, but probably a little on the high side. This is rather surprising, as the effect of the increased slip-stream velocity with the machine climbing with wide-open throttle would presumably be to raise the speed for minimum horsepower required, and the speed for best climb predicted from these curves would therefore be expected to be a little low. In any case, however, the discrepancy is small, and the climbing speed is so nearly the same for all speeds from 50 to 60 miles per hour that the difference can hardly be detected. The climbing speed for No. 1 is computed from the horsepower curves to be 585 feet a minute.



Although, as already noted, no accurate determinations of the rate of climb have been made, such observations as have been taken indicate a maximum rate somewhat less than 585 feet a minute. This is what would be expected, the difference being due to the increased slip-stream effect with open throttle. The curve of horsepower required computed from the JN2 model test, with due allowance for the difference in weight between the JN2 and the JN4H, is also plotted in figure 20. It checks well with the free flight curves except at extreme high and low speeds. From the curves of thrust those for L/D can be derived, and the mean curves for the two machines, together with that for the JN2 model referred to in connection with the lift coefficients, are given in figure 21. The curves for No. 1 and No. 2 are nearly parallel except at small angles, where there appears a marked difference of slope similar to that which characterized the lift curves. Bearing in mind the fact that the curve for No. 1 is undoubtedly more accurate than that for No. 2, it is apparent that the correspondence between the L/D for the JN2 model and that determined in free flight for the JN4H is reasonably good. It is rather dangerous to draw fine conclusions from this correspondence, in view of the difference between the JN2 and the JN4H, but the separation between the curves is hardly greater at any point than the combined possible experimental errors, and the maxima differ by only 2 per cent (if the curve for No. 1 be taken as correct). The indication is that the slip-stream effect and the various crudities of construction on the model (such as the use of round wire interplane struts) are almost exactly counterbalanced by the "scale effect" and by the effect of the omissions of wires, fittings, etc., from the model. In order to obtain quantitative data on the slip-stream effect tests in inclined flight will be necessary.

VELOCITIES IN THE SLIP STREAM.

In order to measure the velocity in the slip stream and compare it with the velocity computed from the results of model tests on the propeller a pitot-venturi head, exactly like the one used for measuring the air speed, was attached to the forward left center section strut. The mouth of the tube was 3.92 feet behind the trailing edge of the propeller, and the axis of the venturi was 2.72 feet radially from the propeller axis. The regular air-speed head and the one in the

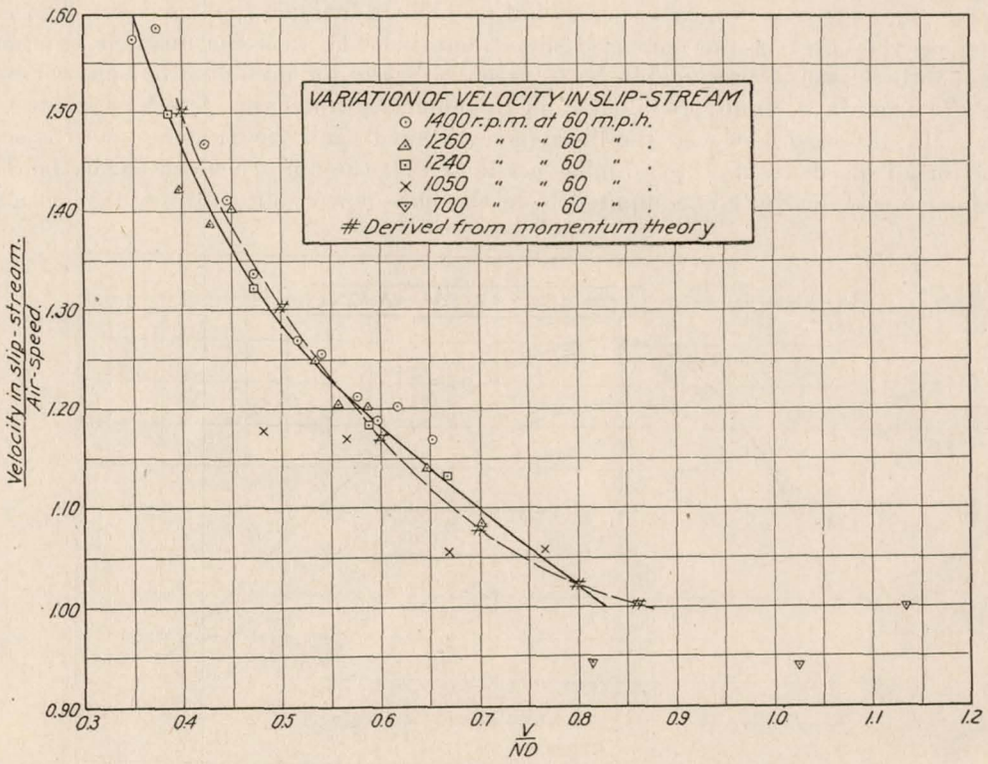


FIGURE 22.

slip stream were both connected to the same meter through the medium of two valves, which made it possible to change readily from one to the other, and to read the air speed or slip-stream velocity, as might be desired. The readings secured in this way are, of course, not highly accurate, as the slip-stream velocity includes a considerable tangential component, the magnitude of this swirl varying with the air speed and engine speed. The air therefore meets the tubes obliquely, and the reading of the meter is probably lower than the true velocity. The error in velocity should not, however, be more than 5 per cent, and the results obtained will at least serve to give an idea of the relation between slip-stream velocity and the factors which control it.

The procedure in these tests was to set the throttle at a fixed position, and to fly the machine at a number of different air speeds without moving the throttle (these flights, of course, were not level). The air speeds used for each throttle setting ranged from 90 to 42 miles per hour, with an occasional dive to 100 miles per hour or a little more. The ratio of slip-stream velocity to air speed for a given propeller depends only on $\frac{V}{ND}$ and these quantities can therefore be plotted against each other. This has been done in figure 22, and it will be noted that nearly all of the points lie close to a smooth curve and that there is no distinct break between the sets of points taken at different throttle openings. The only points which do not fit the curve are those which were taken with the engine throttled down to a very low speed, so low that the propeller was giving no thrust. The slip-stream velocities under this condition were lower than they apparently should have been.

The dotted curve in figure 22 represents the velocity ratio computed from the thrust coefficients by the method described in Report No. 71. This curve checks very well with the other one, and this check indicates that the thrust coefficients as determined in the wind tunnel held for the full-sized machine, and that they are not very materially affected by the presence of the body. Of course, this check is only a rough one. To secure an accurate comparison between the theoretical and actual values it would be necessary to sound the slip-stream thoroughly, measuring the velocities at many points, but previous experiments (by Eiffel and others) indicate that the velocity is nearly constant over a large portion of the propeller disk area, and readings at a single point therefore give some indication of the average condition. It appears that interference between the propeller and the other parts of the airplane can not have a very large effect, as any very notable increase in thrust due to the presence of the body would lead to an increased slip-stream velocity. Experiments at the Royal Aircraft Factory [1] on a pusher biplane, have shown a similarly excellent check between the calculated and measured slip-stream velocities.

The maximum slip-stream velocity with the machine stationary on the ground and the engine turning 1,400 revolutions per minute was about 80 miles per hour. The velocity was very unsteady under the conditions, the meter reading varying by about 6 miles per hour almost instantaneously. This irregularity of flow was no doubt due in part to interference of the ground, but the flow in the slip-stream was in general more irregular, and the velocity fluctuated more rapidly and through a larger range at low speeds than at high.

LONGITUDINAL BALANCE.

The factor on which the longitudinal balance of an airplane primarily depends, and to any variation in which it is always highly sensitive, is the position of the center of gravity of the machine. The first step, then, in any study of balance and of the action of the controls is to determine as accurately as possible the position of the C. G. with regard both to its vertical and its horizontal co-ordinates.

The method used in finding the location of the center of gravity was the usual one of weighing the machine on three pairs of scales, one under each wheel and one under the tail skid, first with the tail skid and wheels on the same level and then with the tail raised. The

[1] Experimental Determination of the Slip-stream Behind the Air-screw of a Pusher: British Advisory Committee for Aeronautics, R. & M. No. 382. 1916.

tail can be raised enough, without overbalancing the machine, to rotate it through an angle of about 15° when the pilot and observer are on board and through 10° when the seats are empty. From the weights thus obtained the center of gravity can be computed with a probable error of less than 0.01 foot in the horizontal co-ordinate and less than 0.03 foot in the vertical.

With a pilot weighing 125 pounds in the front seat and a 165-pound observer in the rear (this being the crew with which most of the tests were conducted), the center of gravity of No. 1 was 1.04 feet behind the leading edge of the lower wing, 2.50 feet behind the leading edge of the upper wing, and 0.28 foot above the thrust line, the axes of reference being taken parallel and perpendicular to the top longeron. The center of gravity of No. 2 was 0.99 foot behind the leading edge of the lower wing, 2.44 feet behind the leading edge of the upper wing, and 0.2 foot above the thrust line. The observer in No. 2 weighed only 125 pounds. If the mean chord be taken as 60 per cent of the way from the lower to the upper chord to allow for the larger area and larger unit lift of the upper wing, the line through the C. G. and perpendicular to the wing chords cuts this mean chord at 39 per cent of its length from its leading edge on No. 1 and 35 per cent on No. 2. This is materially farther back on the wings than the usual location for the C. G.

Since the balance depends on moments about the C. G., a small change of force on the tail planes, acting as it does at a large moment arm, has an important effect, and the angle of the stabilizer is therefore of primary importance. As already noted in the general descriptions of the machines, the stabilizer is supposed to lie flat on the upper longerons. Although the stabilizers were warped the mean chord of the surface was parallel to the top longerons within 0°.2 on both machines.

In order to determine the angle at which the elevator was set at any instant, a sector carrying a scale was fixed to the elevator rocker-arm shaft in the rear cockpit of No. 1, and this sector moved under a pointer fixed to the seat rail. No means of measuring the control position were provided on No. 2, as the arrangement of the elevator-control linkage was different on the two machines, and an entirely new and somewhat more complicated device would have had to be designed. The elevator control wires were adjusted somewhat more tightly than is usual in order to prevent any backlash. The elevator position indicator is shown in position in figure 23.

The force applied to the stick was measured by the instrument illustrated in figure 24. The knob which normally caps the stick was removed, and the slide held between two springs was slipped over the head of the tube. The pilot read the forces directly from the scale. The force indicator was originally fitted with two springs of equal strength, but, as it was found that the force was practically always in one direction, the springs shown in the cut were substituted.

The elevator positions for a variety of air speeds and engine speeds are given by the curves of figure 25. These curves were obtained in the same way as were the points on the slip-stream curve (fig. 22), each one relating to a fixed throttle setting. A fixed throttle setting, rather than a fixed engine power or number of revolutions per minute, is the criterion to which longitudinal balance and stability should be related.

Indicated air-speed (with the speed course correction made) is used directly as the basis for plotting the curves, and variations of air density during the test are entirely neglected. The elevator angles and forces depend primarily on indicated air-speed, since the angle of attack and the flow of air about the machine are functions only of the indicated air-speed and the slope of the flight path. The air density affects the controls in two ways, but both are of minor importance. In the first place, the slope of the flight path for a given throttle setting and indicated air-speed varies with the air density. This factor is insignificant. Secondly, the velocity of the slip-stream and its effect on the controls depend on the true speed and so on the density. This effect, although it is of greater magnitude than the one first mentioned, can safely be neglected except for the large changes of destiny experienced in mounting to great altitudes. All the tests described here were carried out at between 1,500 and 4,000 feet.

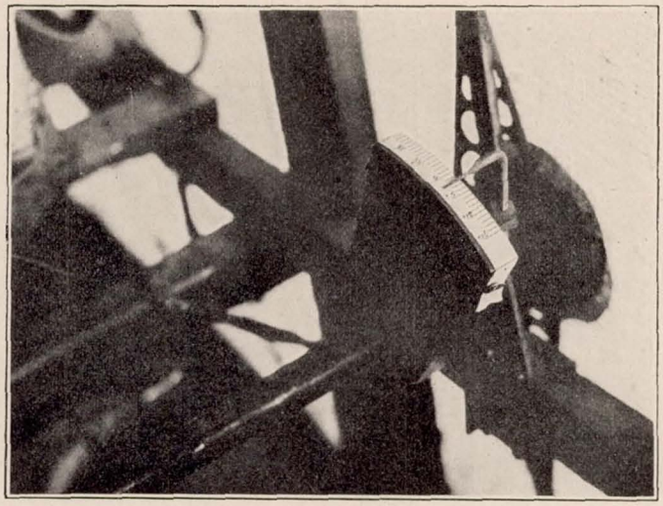


FIG. 23.—ELEVATOR ANGLE INDICATOR.

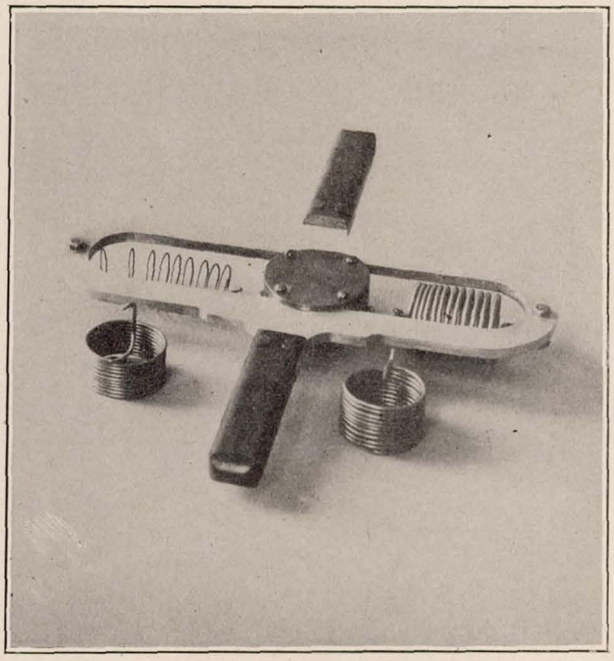


FIG. 24.—ELEVATOR FORCE INDICATOR.

Curve No. 1 relates to flight with wide-open throttle, No. 5 to gliding descent with the engine throttled down to idling speed. The elevator angle is referred to the top longerons as a datum line, and is taken as positive when the trailing edge of the elevator is pulled down. It will be observed that the curves all have the same general form, and that the positive angle of elevator setting for equilibrium at any given speed decreases progressively as the engine speed decreases. This is due to the slip-stream effect on the stabilizer and to the location of the center of gravity above the thrust line, both of these things tending to cause the airplane to nose down to a smaller angle of incidence as the throttle is closed and therefore requiring that the elevator be pulled up in order to maintain the same angle of attack and the same air-speed. Translated into practical terms, this means that, if the stick were locked in position while the

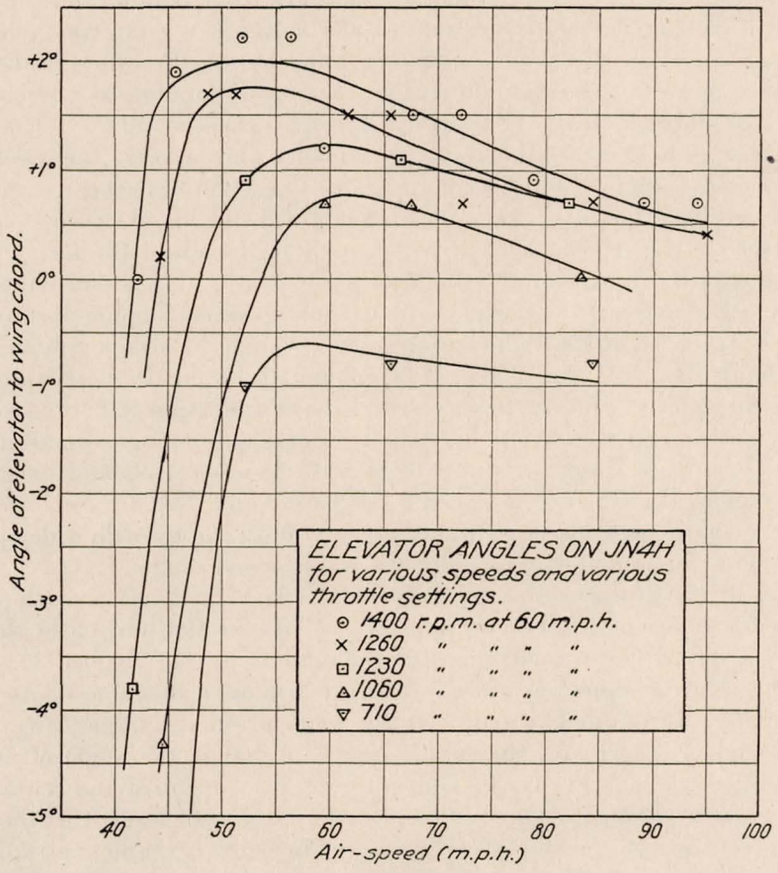


FIGURE 25.

machine was climbing with open throttle, so that the elevator setting could not change, whatever might be the forces acting on the control surface, and the throttle were then closed the nose of the airplane would drop, and would continue to go down at least until the speed of the dive reached 90 miles per hour, and probably until the airplane passed the vertical and attained an up-side-down position. It is, of course, desirable that the nose should drop when the engine is throttled or cut off completely rather than that the machine should stall, but it is also desirable that the nosing down process should stop at a determinate point instead of continuing indefinitely. An airplane ideally balanced and ideally stable would continue at some speed within its normal range and at a normal inclination of path, with the longitudinal control locked whatever might be done to the throttle. The condition of locked control, of course, is only one of several which may occur. Others, even more important, will be discussed later in this section.

It is characteristic of the curves of figure 25 that they have a maximum point, and that their slopes at high and low air-speeds are accordingly of opposite sign. The effect of this change of slope can best be illustrated by two concrete examples. If an airplane is flying with the throttle setting corresponding to curve No. 3, and at a speed of 65 miles per hour, and if the stick is then suddenly pushed forward by an amount sufficient to increase the elevator angle by 0°.2 and locked in this new position, the primary effect will be to nose the airplane down, decreasing the angle of incidence and increasing the speed, since the pulling down of the elevator sets up an unbalanced upward force on the tail, and this gives rise to a diving moment about the center of gravity. By the time the speed has increased to 80 miles per hour the proper elevator setting for equilibrium is 0°.7, but the surface is locked at 1°.2. There is, therefore, still an unbalanced diving moment, larger now than before, and the speed continues to increase with a constantly steepening path. Manifestly this is an unstable condition, and it may be dangerous if the pilot is not vigilant. Suppose, on the other hand, that the initial speed was 50 miles per hour, this being less than that corresponding to the maximum elevator angle, and that the elevator was pulled down 0. 2° and locked as before. The first effect, just as in the other case, is to decrease the angle of incidence and increase the speed. By the time the speed has increased about 1 mile per hour, however, a point is reached where the machine is in equilibrium with the new elevator setting, and it will then continue in steady flight at this slightly higher speed. Gusts which change the angle of attack of the airplane have just the same effect as a sudden change in the angle of the elevator. If an airplane which is flying with the control locked at a speed corresponding to the negatively sloping portion of the elevator position curve is struck by a gust which decreases its angle of attack the angle will continue to decrease without limit. If the speed is low enough to lie on the positively sloping portion of the curve the airplane will return to its original speed and angle of trim as soon as the effect of the gust has passed. A positive slope therefore makes for longitudinal stability. It will be noted that the range of speed for stable flight with fixed controls and fixed throttle setting becomes wider in general as the engine speed is decreased, and that, for the lowest curve (engine idling), there is no sharp negative slope at any point. With the throttle wide open, on the other hand, the machine is unstable for practically the whole speed range.

An ideal set of elevator position curves would have a small positive slope at all points, and the curves for different throttle settings would be parallel and close together. Such a set is shown in figure 26 for comparison with the actual curves of figure 25. It is not desirable to have the positive slope very large at any point, as a machine characterized by such curves is difficult to control quickly, requiring the application of a larger force, and the moving of the stick through a longer arc, than is desirable to change the angle of attack. The stability with fixed controls can always be controlled by movement of the center of gravity, the stability being greatest when the C. G. is farthest forward with respect to the wings.

The sudden reversal of the slopes of the curves in figure 25, and the rapidity with which the elevator setting changes at low speeds, are due to the change of the center of pressure travel on the wings. This travel becomes less unstable as the angle increases and the effect, when combined with the movements due to the tail, is to give to the whole machine a high degree of statical longitudinal stability at low speeds.

At all speeds ordinarily used the elevator angle decreases as the angle of attack decreases, so that it is necessary to hold the stick farther back to fly at high than at moderate speed. Of course, it is not possible to go directly from one condition to the other, as, for instance, to decrease the angle of attack by pulling the stick back while flying in equilibrium at a moderate speed. The effect in that case would be the opposite of the one desired, and it is necessary, when the angle is to be decreased, first to push the stick forward, nosing the machine down until the desired angle is reached, and then to pull it a little farther back than its original position in order to keep the machine in the attitude thus assumed.

For the sake of comparison the curve of elevator angles for a JN2 has been computed from tests made at the wind tunnel of the Massachusetts Institute of Technology [1] and is given in figure 27 together with a reproduction of the curve for the JN4H with the engine idling. In computing the curve for the model the center of gravity was assumed to be in the same position with regard to the mean chord of the wings as in JN4H No. 1. The differences between the JN2 and the JN4H are not of a nature which would be expected materially to affect the balance and stability, except that the stabilizer on the former is set at $-3°$ to the wing chord, while that on the latter is at $-2°.3$. This accounts for a part, but only a part, of the relative displacement of the two curves. It will be noted that the model test would have led to a prediction of tail-heaviness, the opposite of the condition existing. This difference can be attributed

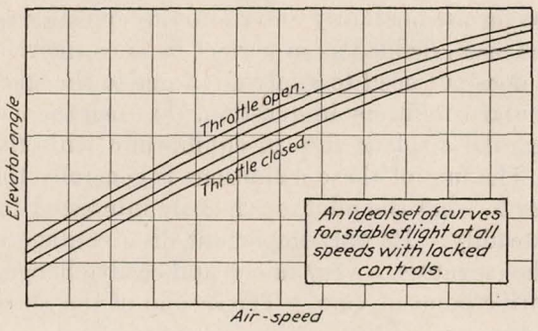


FIGURE 26.

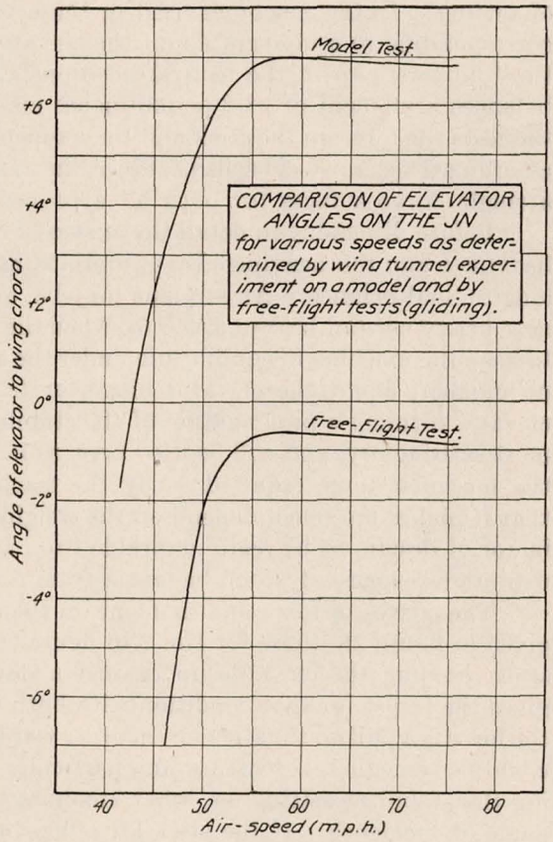


FIGURE 27.

to the fact that the tail of the model was made up as a flat plate cut from sheet metal and the difference between inclinations of the zero lift lines of the stabilizers in the model and the full-sized machine was therefore much greater than was the difference in the settings of their chords. The large error in balance resulting from this error in tail construction points again to the necessity of minute accuracy in constructing the sustaining and control surfaces of wind tunnel models.

The two curves of figure 27 are of almost exactly the same form and it appears probable that, were it not for the error noted above, they would be close enough together so that the balance of the air plane and the control position in gliding flight, when there is no slip-stream effect, could be closely predicted from the model test. The present experiments and others of a similar nature on many different types of machines will provide the necessary data for

[1] Bulletin Airplane Engineering Dept. U. S. A., June 1918, p. 89

correcting the wind tunnel results for slip-stream effect and so for predicting the balance of an airplane at full power before it is built.

The discussion so far has been confined to the case of stability with locked controls. This of course, is rather an uncommon case at present as very few machines, especially of nonmilitary type, are fitted with means for locking the stick in position. The provision of a device for this purpose is highly desirable from some standpoints, and may become the usual thing at some future date, but there are other cases which, as already noted, are of more importance at present.

If the elevator is left free and uncontrolled it will take up a position in which there is a small moment about the elevator hinge, due to the air forces acting on the surface, tending to decrease the angle. This corresponds to an upward force on the elevator and is required to balance the weight of the member, which produces a moment tending to increase the angle of setting. In the machines used in these tests a force of $8\frac{1}{2}$ pounds at the top of the stick, corresponding to a moment about the elevator hinge of 206 pound-inches, was required to hold the "flippers" up in the neutral position. A force of 1 pound at the upper end of the stick balances a moment of 24.2 pound-inches about the elevator hinge. In plotting the results of the tests the force on the stick and the moment about the elevator hinge have both been plotted as ordinates against air speed. Since the ratio between the forces and the moments is fixed a single curve suffices for both by a proper adjustment of scales.

Before discussing in detail the curves of control force, a digression on the definition of nose heaviness and tail heaviness is appropriate, as these terms constantly enter into any question of longitudinal balance. An airplane may be, and has been, defined as in perfect balance (neither nose heavy nor tail heavy) either (*a*) when the pilot does not need to apply any force to the stick to keep the machine in equilibrium under the particular conditions in question, (*b*) when there is no moment about the elevator hinge, or (*c*) when the airplane flies in equilibrium with the elevator forming a prolongation of the stabilizer. The first of these definitions is generally the most satisfactory, and will be used here, as it relates to what the pilot is primarily interested in, the muscular force required to fly the machine steadily. Its only important disadvantage is that it makes too much depend on the weight of the elevators, a very minor and easily changed factor of design, to be really desirable from a scientific point of view. The second of the three definitions suggested would be better from this standpoint.

The curves of force and moment on the elevators of No. 1 for various throttle settings are given in figure 28, those for No. 2 in figure 29. The positive sign corresponds to a pull on the stick, holding the elevator up against a downward force. The curve marked "level flight" gives the forces for that condition with both air speed and throttle setting varing. In all cases the force is a pull on the stick, or, in other words, the airplane is nose heavy. This nose heaviness could be remedied, at least for any particular speed, or reduced to any desired extent by changing the stabilizer setting, or, what amounts to the same thing, by rigging the wings at a larger angle of incidence. If the stick on either one of the machines used in these tests is released, it will move forward from the equilibrium position and the machine will go into a dive with the throttle wide open. Releasing the stick during gliding descent also throws the airplane into a dive, the speed and steepness of which rapidly increase, apparently without limit.

With free controls, just as with the controls locked, stability is indicated by the slope of a curve, but it is the curve of control forces in this case instead of that of control positions. When the slope of the curve of forces is negative, as it is at low speeds in figures 28 and 29, the machine is stable with free controls, provided that the line of zero force on the stick intersects the curve of forces, as any change of speed would set up moments which would cause the elevators to move in the proper direction to restore the machine to its original attitude. When, on the other hand, the slope is positive the equilibrium is unstable and can only be restored, once it is upset, by the intervention of the pilot. It is evident from the curves that with free controls, just as with the controls locked, the statical longitudinal stability is greatest at low speeds of flight, that the machine becomes unstable at speeds in the neighborhood of the maximum attainable, and that the stability is greater in gliding than with the throttle open.

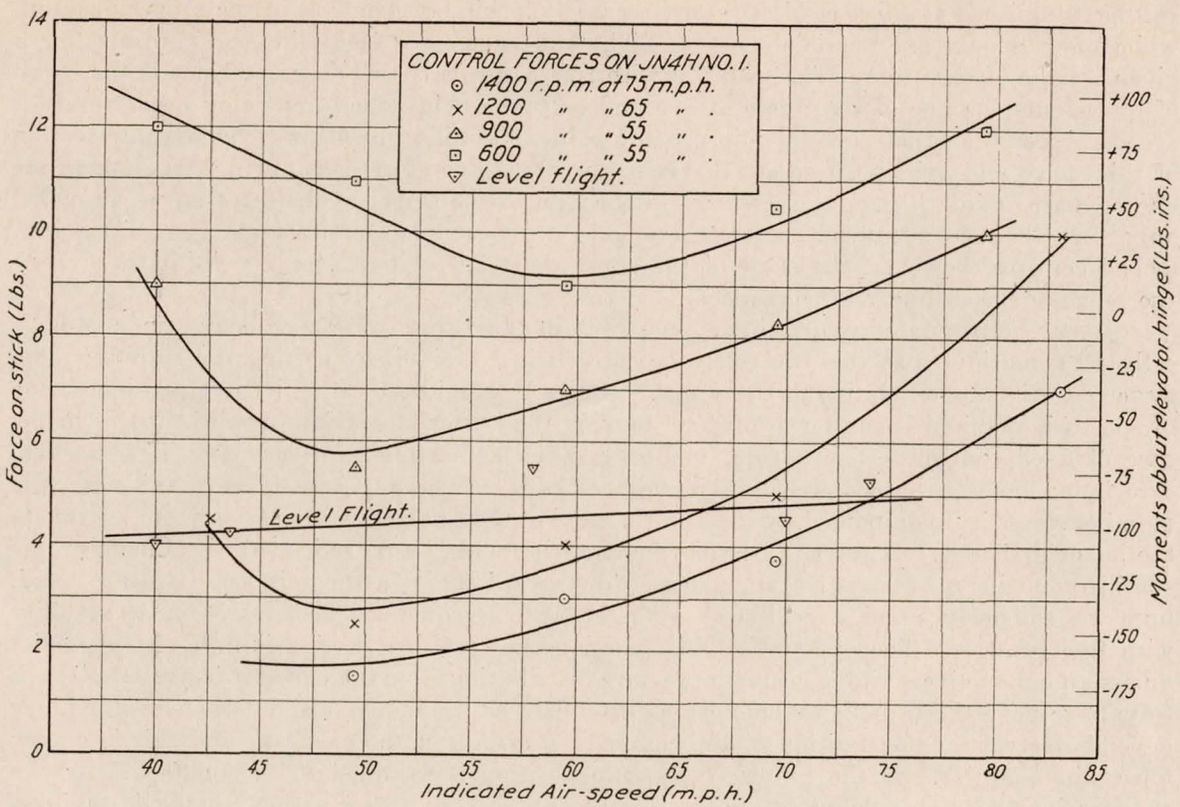


FIGURE 28.

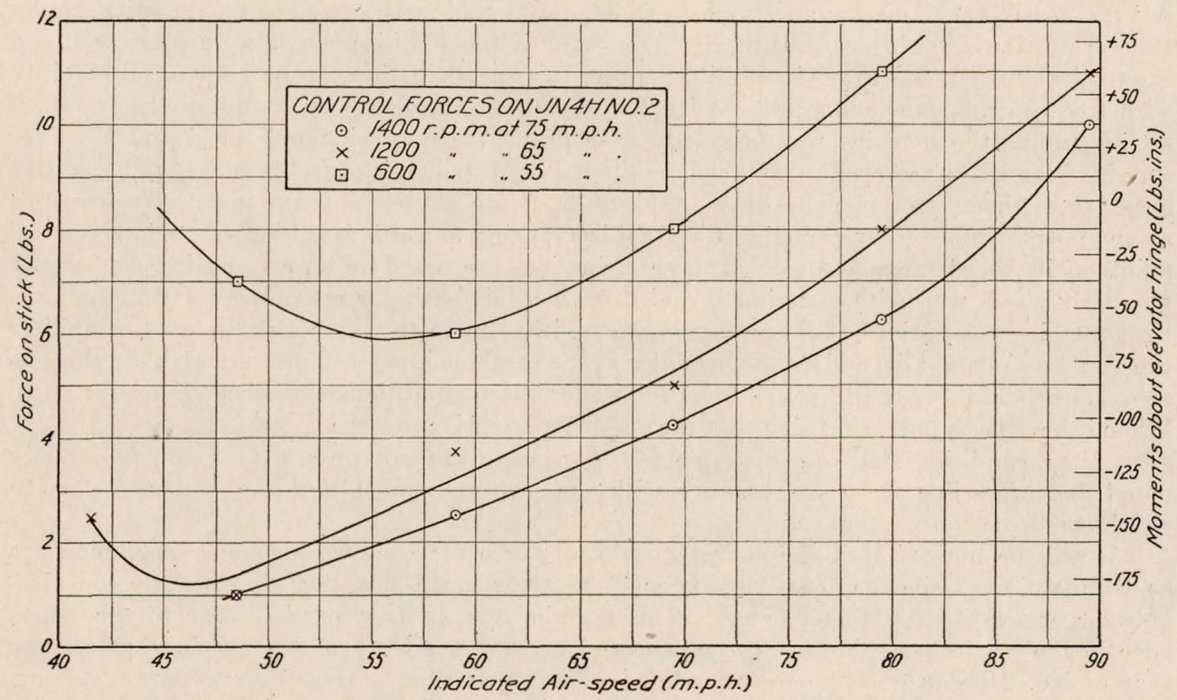


FIGURE 29.

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The chief difference between statical stability with locked and free controls is that equilibrium can be established at any speed in the former case by locking the controls in the proper position, while there is only one possible speed of flight and angle of attack with free controls (for a given weight of elevator). The stability with free controls is therefore sufficient if the curve of forces cuts the line of zero force at one and only one point, the force being negative at all speeds higher than that corresponding to the point of equilibrium defined by the intersection of this curve and axis, positive at all speeds lower. It therefore does not matter if there are one or more "kinks," involving changes in the sign of the slope, in the force curve, provided only that they do not reach or cross the axis. For completely satisfactory stability with locked controls, however, the slope of the curve must be positive at every point throughout the range of speeds likely to be reached.

As has been pointed out, the machines used in these tests were nose heavy under practically all conditions, but this can easily be corrected, if desired, by setting the stabilizer at a larger negative angle relative to the wings. If greater stability or stability over a wider range of speeds is required it can be secured by moving the center of gravity forward, just as in the case of fixed controls. The natural tendency, when a machine is nose heavy, is to seek to cure it by moving the center of gravity farther back. Where, however, as in this case, the nose heaviness is accompanied by instability, moving the C. G. aft will only serve to aggravate the latter difficulty. If the C. G. is moved at all it should be moved forward. Changing the stabilizer setting so as to give an increased downward force on the tail, on the other hand, improves the balance and, as will be shown later, also has some beneficial effect on the stability with free controls. The exact effect of changing the stabilizer setting is difficult to predict unless an exhaustive series of tests on pressure distribution over the elevator is available (such tests have never been made except for one machine), as the moment about the elevator hinge depends largely on the position of the center of pressure on the elevator, and this is a very uncertain quantity. If the center of pressure position is assumed to be unaffected by the changes in elevator angle to secure equilibrium at a given speed with a changed stabilizer setting, the alteration in moment about the hinge, due to the different stabilizer angle, is almost exactly proportional to the square of the speed, as the change in elevator angle for equilibrium is very nearly the same for all speeds. The slope of the curve of forces on the stick, under these conditions, would decrease in algebraic value if the stabilizer angle were decreased, and the tendency would be toward stability. From this the deduction can be drawn that stability with free controls can not be obtained at any given speed merely by changing the stabilizer setting unless the machine was originally nose heavy at the designated speed and all lower speeds of flight. Furthermore, an airplane the curve for which is unstable (i. e., has a positive slope) throughout the range of normal speeds of flight can not be made stable with free controls at any speed whatever by changing the stabilizer setting unless it is initially nose heavy at all points of its speed range. Although these deductions are based on an assumption not strictly true they check well with experiment and furnish a fair basis for reasoning. It follows from the foregoing conclusions that the maximum positive angle to which an adjustable stabilizer can be moved should depend on the behavior of the machine in a steep descent with the throttle open. For stability, the force on the stick under those conditions should always be a push. When it becomes a pull it is a sign that the stabilizer angle is too large.

If the conditions laid down in the last paragraph are not observed it will, as already noted, be impossible to secure stability with the stabilizer alone, and the center of gravity will have to be moved forward.

It will be noticed that the curves of control force for the two airplanes in gliding are nearly identical, while the negative moments about the hinge with throttle open are considerably larger for No. 1 than for No. 2. This difference is at least partially due to the difference in the vertical coordinates of the center of gravity, the C. G. of No. 1 being higher than that of No. 2 because of the reserve tank in the upper wing. The center of gravity being farther above the thrust line in No. 1, the thrust on that machine produces a stalling moment

about the C. G., and this has the effect of making the machine less nose heavy than it would otherwise be.

It is desirable that the pilot of an airplane should be able to release the controls at any time without causing the machine to go into a steep dive or to stall badly. In order to fulfill this requirement the center of gravity should be materially farther forward with respect to the wings than it was in the particular airplanes which were the subjects of these tests, and the stabilizer should be set at such an angle to the wings that the machine will be in equilibrium with the controls free and the engine throttled at a speed well within its normal range (60 miles per hour would be a good figure for an airplane of the type and performance of the JN4H). Exact recommendations as to the position of the C. G. can not be made without further tests, but it is probable that 28 per cent of the way back from the leading edge on the mean chord of the wings will be found a satisfactory location. The negative angle of the stabilizer with respect to the wings should be larger in these machines than inthose in which the stabilizer section is symmetrical about a horizontal plane. A stabilizer with a flat lower and a cambered upper surface, such as that ont he JN4H, has its zero lift line at an angle of from 2° to 4° to its chord, and it is the zero lift line which should be considered in choosing the setting.

In order to put to the test these theories as to the cause and cure of instability and poor balance, airplane No. 1 was rerigged with the stagger reduced by 3 inches, and with the rear of the stabilizer blocked up so that its chord was at a negative angle of 1°.6 to the top longerons, or 4° to the wings. The reduction of the stagger by moving the upper wing backward has practically the same effect as has moving the center of gravity forward.

Although the tests with this new arrangement have not as yet been carried far enough to make it possible to plot a set of curves, it was very apparent that the nose heaviness of the machine was much diminished and that the stability, both with free and fixed controls, was improved. The machine was still unstable at high speeds, but much less so than before. It was dived to a speed of 115 miles per hour with the throttle half closed, and the pull on the stick at this speed was only 10 pounds. There was no difficulty in taking off or landing, and the performance of the machine was not modified in any other respect. It is believed, as a result of these tests, that it will be found possible by further changes of the same nature to secure complete statical stability of the JN4H at all speeds without incurring any counterbalancing disadvantages.

Longitudinal balance of the De Haviland.

In order to have data on another airplane for purposes of comparison, and also to secure definite information on the effect of an adjustable stabilizer, the experiments which have been described above were repeated on the De Haviland 4 with Liberty engine. The method pursued in the first series of tests on this machine was identical with that already described, and the curves of control position, force, and moment for various throttle settings are given in figures 30 and 31. The force required at the top of the stick to balance the weight of the elevator was 3¾ pounds, and a force of 1 pound on the stick corresponded to a moment of 24.6 pound-inches about the elevator hinge. The "gearing" of the control was therefore practically identical with that in the JN. The scale of abscissæ may not be strictly accurate, as the air-speed meter on this machine was never calibrated on the speed course, but it probably would not be in error by more than three or four miles an hour at any point.

It appears from these curves that the DH4 possesses statical longitudinal stability both with fixed controls and with free controls, and that the trimming speed for any given condition increases as the engine speed decreases. If, for example, the elevator is locked at +3° with the throttle open the machine will fly at 82 miles per hour, and will automatically return to that speed if any disturbance causes a momentary deviation from it. If the engine is then throttled down to the idling condition, leaving the control still locked at +3°, the nose will drop and the steepness of the flight path will increase until the speed of 114 miles per hour is attained. The airplane will then continue to descend steadily at this speed on a flight path of constant slope. There will be no tendency, as in the other airplanes which have been discussed, to dive more and more steeply without limit.

Much the same statements can be applied to flight with free controls, except that in this case there is only one trimming speed for a given stabilizer angle and throttle setting. Here, again, the trimming speed increases as the throttle is closed.

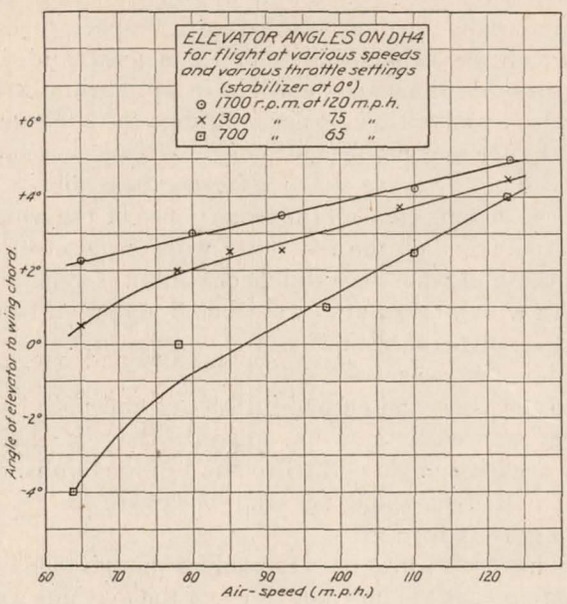
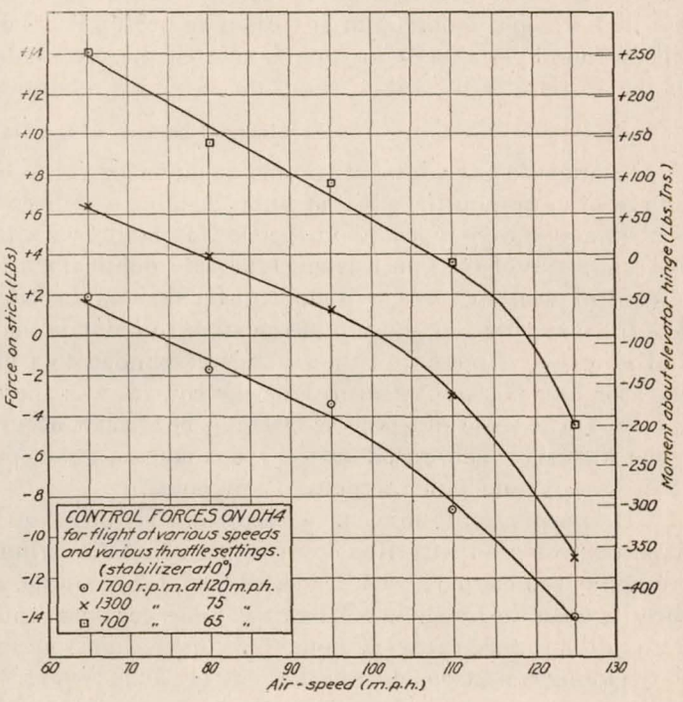


FIGURE 30.

It is obvious that the airplane of the future must have a high degree of inherent stability, so that it can be flown "hands off" for considerable periods in calm air. Since it is not desirable that the machine be limited to a single air speed for a given throttle setting, some means must be provided for changing the trimming speed. This can be done either by a device for locking the controls in any desired position or by making it possible for the pilot to adjust the stabilizer angle while in flight. The first of these alternatives has the advantage that it is easy and quick to operate, as the stick can be made with a lock instantaneously operable by the pressure of a finger. The locking should apply only to the fore-and-aft motion, the stick being left free to move from side to side in order that the pilot may correct disturbances of transverse equilibrium without releasing the lock, and, also, so that the ailerons may be free to move when struck by gusts, so giving a certain degree of "automatic warp." If an adjustable stabilizer is provided, it takes longer to change the angle for a new trimming speed than it does to move the stick and lock it in a new position. The adjustable stabilizer has, however, the very great advantage that the stick is left entirely free for control, and it can therefore be used to reduce the strain on the pilot even when the air is too rough or when the machine is too near the ground to permit of releasing or locking the stick.



The effect of the adjustment of the stabilizer is shown by figures 32 and 33, which give the curves of control forces and moments for level flight with three different stabilizer settings. Figure 33, giving the control forces required and the trimming speeds with free controls for the several settings, is the more important of the two. It appears from the curves there given that the statical longitudinal stability with free controls diminishes rapidly as the stabilizer angle is increased, and that, when the neutral line of the stabilizer is set at $+1° 30'$ to the wing chord, the machine is statically unstable at low speeds. Figure 32, on the other hand, indicates that the degree of stability with locked controls is substantially independent of stabilizer setting, the three curves being very nearly parallel to each other. This is what would be expected

from model tests and from theoretical considerations, some of which were developed in the preceding section of this report.

The trimming speed increases as the stabilizer angle increases, slowly at first and then very rapidly. A change of angle from $-1°\ 30'$ to $0°$ only raises the trimming speed with free controls from 71 to 86 miles per hour, but only about $0°\ 40'$ further change in angle is required to increase the trimming speed from 86 to 120 miles per hour. Since so small a change of angle has so large an effect it is necessary, in order to gain the full benefit of an adjustable stabilizer, that the adjustment be through a screw or other slow-motion device with a minimum of backlash, so that the angle can be regulated with great exactness. The backlash on the DH4 tested was about $0°\ 15'$.

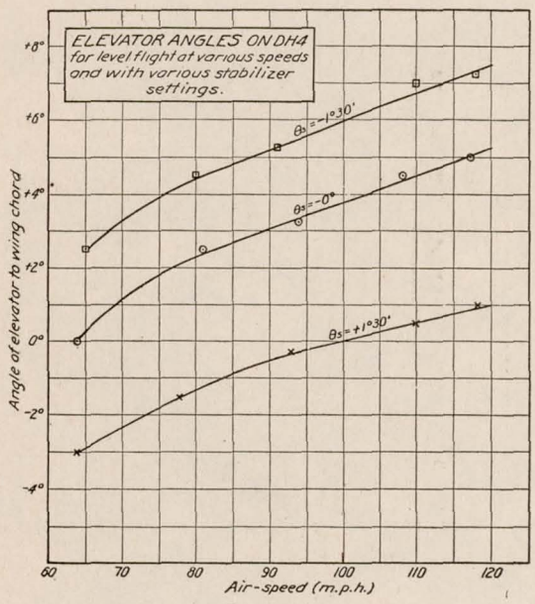


FIGURE 32.

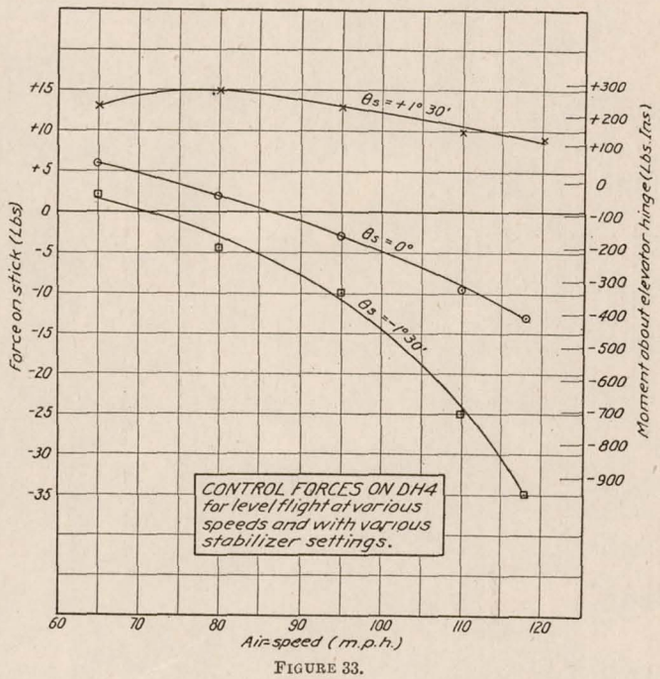


FIGURE 33.

The provision of an adjustable stabilizer on the DH4, and the range of angles chosen for the adjustment, were largely due to the distance between the center of gravity and the observer's cockpit and the gasoline tank, a small change of weight in the rear cockpit having a large effect on the balance of the machine. For the conditions existing when these tests were carried out (170-pound observer, no heavy instruments, guns, photographic apparatus, or other equipment in the rear cockpit, and gas tank two-thirds full) the maximum positive adjustment of the stabilizer would never be required.

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REPORT No. 71

SLIP-STREAM CORRECTIONS IN PERFORMANCE COMPUTATION

BY

EDWARD P. WARNER

Aerodynamical Laboratory, National Advisory Committee for Aeronautics, Langley Field, Va.

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REPORT No. 71.

SLIP-STREAM CORRECTIONS IN PERFORMANCE COMPUTATION.

By EDWARD P. WARNER.

In computing the performance of an airplane, the values taken for the slip-stream correction have a very marked effect on the results, both as regards the speed required for flight at a given angle of attack and as regards the horsepower required, and a mistake in estimating the magnitude of the correction factor may cause considerable errors in the preliminary estimate of performance attainable. Notwithstanding the importance of the slip-stream effect relatively little study has been devoted to it and the proper way of treating it still remains largely uncertain. This lack of knowledge as to the magnitude of the correction and its effects is amply attested by the wide variation among the methods employed by designers engaged in the making of performance computations. Some have ignored the correction entirely. Others, seeking a slightly greater accuracy but not desiring to embark on too laborious a set of computations, have made an over-all allowance, increasing the total resistance of the machine (including both parasite resistance and wing drag) by 10 per cent or 15 per cent. Such a device is frequently employed when performance is to be computed directly from a wind-tunnel test on a model of the complete machine, and when only the total resistance is known, no data on the resistance contributed by different parts of the structure being available. As the proportion of the total resistance which lies in the slip stream varies widely between different types of machines, this method can manifestly lead to nothing more than a very rough approximation. The next step, to further increase the exactness of the performance computations, is to consider the resistance broken up into two parts; that due to members inside and that due to members outside the slip stream, and to treat these two parts as having different relative air speeds. The speed used in computing the resistance of the parts outside the slip stream area is equal to the air speed of the machine; that used for the parts inside the slip-stream is somewhat higher. The amount of the difference between the two has been much in dispute, but the corrections generally applied range from 10 per cent to 20 per cent. That is to say, the velocity is considered to be from 10 per cent to 20 per cent greater inside than outside the slip stream, and the resistance of an object in that area is therefore taken as from 21 per cent to 44 per cent greater than the resistance of the same object would be if it were removed from the zone of influence of the propeller draft.

Whatever the value that may be taken for the correction factor, it is almost invariably considered to remain constant at all speeds of flight, and it is in this assumption that the greatest source of error lies. When the engine is kept running at full throttle, and all the reserve power is used in causing the machine to climb, the air speed being relatively low, the ratio of slip-stream velocity to velocity of advance will quite evidently be considerably higher than when the flight path is horizontal, with a higher speed of advance or with a throttled engine. The exact manner of the variation of slip-stream effect will be taken up a little later.

We may attack the problem of the slip-stream correction in either of two ways, both of which we shall discuss. In the first place, we may base our corrections on wind-tunnel tests of propeller models. Unfortunately, there is very little data available on the velocity of the flow of the air behind a propeller under test. Secondly, we may depend on pure theory, determining the mean slip-stream velocity from energy considerations. While this is not strictly valid, it affords an interesting means of obtaining data for comparison, and of extending the experimental results.

EXPERIMENTAL RESULTS.

Measurements of slip-stream effect for model propellers have been made by Eiffel, at his laboratory near Paris, and by Riabouchinsky at Koutchino. Eiffel's results are the more valuable, as the propeller used during the tests was more nearly like those used on aircraft at the present time than were the models employed at Koutchino.

It should be noted that all these experiments deal with propellers tested with no other objects in their neighborhood, and that the results might be materially modified by the mutual interference of the propeller and the other parts of the machine. This is particularly true of the body, inasmuch as it is very close to the propeller and is immediately behind the least efficient portion of that member, so that it has somewhat the same effect of stream-lining the hub and guiding the air across the more effective portions of the blade as has a spinner in front. The effect of the body on the propeller would then be such as to neutralize, at least in part, the increase of body resistance caused by the slip-stream. This effect would apply primarily to the body, the resistance of which, if it is well designed, is a relatively small part of the total parasite resistance in the slip-stream. The effect of the struts, tail surfaces, and other members on the action of the propeller would probably be so small as to be negligible, thanks to their distance behind the propeller and to the fact that they lie behind the effective portion of the blades rather than directly behind the hub.

The ratio of slip-stream velocity to velocity of advance, like every other factor or propeller performance, is, for geometrically similar propellers, a function of the nondimensional ratio V/ND. Since it is necessary to apply to widely different propellers the data obtained by tests of two or three special cases we must seek some means of comparison, and this means is provided by the provisional assumption that the ratio of slip-stream velocity to flight velocity at the speed of maximum propeller efficiency is the same for all propellers. We may then consider the slip-stream effect to depend on the ratio of V/ND to $(V/ND)'$, or, for a given propeller diameter and engine speed, on V/V', where V is the actual speed of flight and V' the speed for maximum propeller efficiency at the same number of revolutions per minute. This is the only method open to us if we rely solely on experimental data, but we shall see later that the use of the momentum theory makes it possible to actually compute the slip-stream effect for a given propeller, and that the magnitude of this effect varies somewhat with blade form, blade width, number of blades, pitch-diameter ratio, etc.

Eiffel's experiments [1] were performed on his propeller No. 9, which has quite a normal blade form, with straight trailing edge and leading edge so curved as to give a maximum blade width approximately three-quarters of the way out from hub to tip. The pitch at all points was 0.7 of the diameter, and the maximum efficiency (75 per cent) was secured when V/ND was equal to 0.6, corresponding to a speed of flight of roughly 105 miles per hour with a Liberty engine turning 1,700 revolutions per minute and a two-bladed propeller 9 feet in diameter. The ratio of effective pitch to diameter for best efficiency therefore was not very far from current practice.

The air velocity in the slip-stream was determined by pitot tube measurements at five points, placed at 0.4, 0.6, 0.8, 0.96, and 1.1 times the radius from hub to tip. That is, the last point was actually slightly outside of the propeller disk area. To determine the extent to which the air spreads out and the added velocity disappears as the distance from the propeller is increased, three such sets of points were tried, the first being only 0.04 of the propeller diameter behind the plane of the trailing edges of the propeller blades, the second being located 0.2 of the diameter behind that plane, and the third being separated from the propeller by a distance equal to its diameter.

The conclusions to be drawn directly from the results of these tests may be tabulated briefly as follows:

(*a*) The slip-stream velocity is a maximum at a radius of about 0.6 of the distance from hub to tip.

[1] "Nouvelles Recherches sur la Resistance de l'Air et l'Aviation," by G. Eiffel: Paris, 1914; p. 333.

(*b*) At low speeds of advance and large slip percentages the slip-stream velocity drops off very rapidly near the edges of the propeller disk. In the case under examination, at moderate translational speeds ($V/V' = 0.4$ to $V/V' = 0.6$), the added slip-stream velocity (i. e., the difference between Vs and V) at the radius 0.96 was from 40 per cent to 70 per cent less than that at radius 0.8. At higher speeds of advance, a decrease in slip-stream in going out from one of these points to the other is still noticeable, but it is much less abrupt and less marked.

(*c*) At points which are neither very near to the center nor to the edge of the propeller disk, the velocity varies very little with distance from the propeller, at least within the limits of these experiments. At the higher speeds of translation, there is a slight tendency for the velocity to increase as the distance from the propeller increases.

(*d*) Near the center of the propeller the velocity drops off somewhat, but not nearly so much or so abruptly as it does near the tip.

(*e*) At low velocities of advance, the velocity near the center of the propeller disk increases considerably as the distance from the propeller increases.

(*f*) Near the edge of the slip-stream, the velocity is greatest very close behind the propeller. On going back from the propeller the velocity decreases quite rapidly for a short distance, and then, on going still farther away, shows a tendency to increase slightly. (*e*) and (*f*), taken together, indicate that the slip-stream diameter is nearly independent of distance from the propeller, but that it contracts rapidly for a short distance passing through the propeller. The point of minimum section having been reached, the slip-stream begins to expand in cross-section, but only very slowly. We shall not go far astray if we consider the slip-stream velocity and section to be independent of the distance from the propeller.

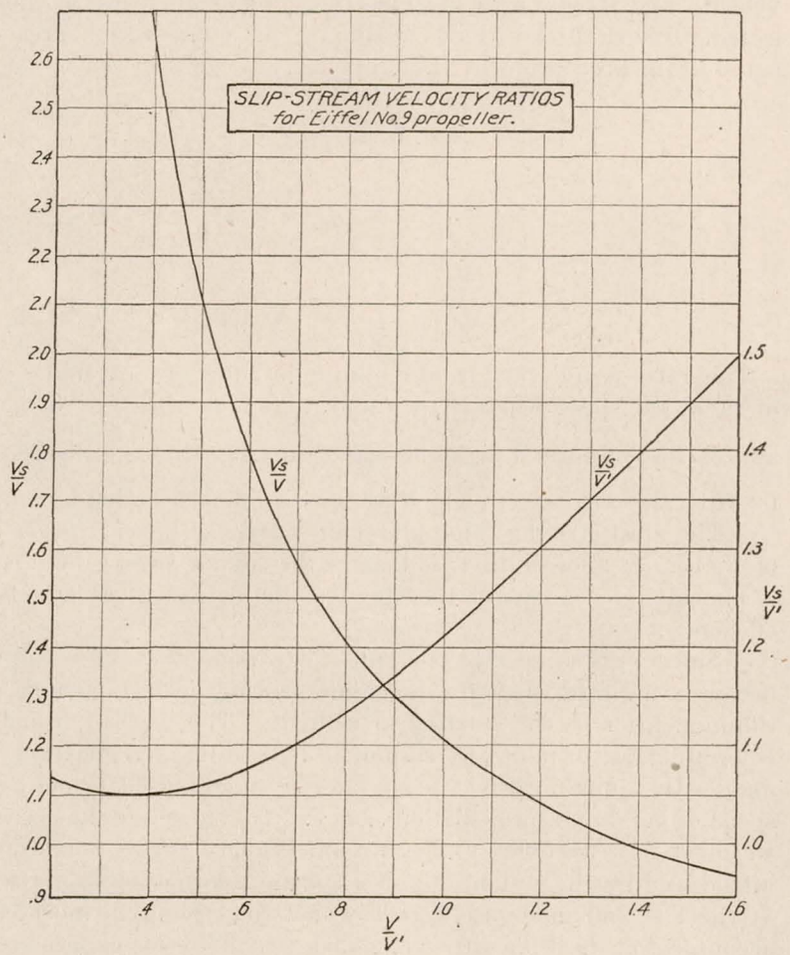


FIG. 1.

Summing up, it appears that we shall secure reasonable results if we take the slip stream as having 0.9 the diameter of the propeller and assume the velocity to be constant over the stream so defined. Mean values, obtained in this way, of V_s/V and V_s/V' have been plotted against V/V' in figure 1, V and V' being the actual velocity of advance and the velocity of advance for best propeller efficiency, as before, V_s being the velocity in the slip stream. N and D are assumed to remain constant throughout. Any change in these quantities will necessitate a recomputation of V'.

Although the above assumption as to slip-stream diameter may be accepted as registering sufficiently closely with experimental results, it can be shown theoretically that the diameter of the stream should vary with slip ratio, or, for a given engine speed and propeller diameter, with the speed of flight. R. E. Froude has shown that the increase in velocity of the fluid before it reaches the propeller should be exactly equal to the added velocity imparted after passing through the propeller, or, using algebraic symbols, that $V_1 - V = \frac{1}{2}(V_s - V)$, where V is the speed of flight, V_1 the indraught velocity, and V_s the slip-stream velocity. Since the same mass of fluid passes every point along the stream in a unit of time, the product of velocity and stream area must be the same at all points if compressibility of the fluid be neglected. We shall then have, assuming the cross-section area of the inflowing current to be equal to the area swept by the propeller:

$$A_s \times V_s = \frac{\pi D^2_s}{4} \times V_s = \frac{\pi D^2}{4} \times V_1 = \frac{\pi D^2}{8}(V_s + V)$$

$$D_s^2 \times V_s = \frac{D^2}{2}(V_s + V)$$

$$\frac{D_s}{D} = .71\sqrt{\frac{V_s + V}{V_s}} = .71\sqrt{1 + \frac{V}{V_s}}$$

This ratio would vary from a minimum value of 0.71, under static conditions, to a maximum of 1.0 at the speed where $V_s = V$ and there is no thrust. As neither of these conditions is ever approached in normal flight, we can safely say that the theoretical value of $\frac{D_s}{D}$ will not wander far from the one (0.9) to which we have already been led by empirical data.

The most striking thing about the curves of figure 1 is the remarkable degree of constancy of V_s/V'. It appears that, so long as the engine speed is kept constant, the slip-stream velocity is almost independent of the speed of flight, except at speeds well above that of maximum efficiency.

Since V_s is so nearly constant, it is evident that V_s/V will increase rapidly as V decreases, becoming infinite when the machine is being held stationary on the ground with the engine running, prior to the starting of a flight. The method, which I have already mentioned, of computing performance by assuming V_s/V to have a constant value of 1.15 or 1.2 is therefore manifestly quite incorrect except for a single speed somewhere in the neighborhood of the speed of maximum propeller efficiency. To determine the correction factor for any other speed we must have recourse to slip-stream velocity curves similar to those of figure 1. The error introdueed by the assumption of a constant correction factor will obviously be most important at the low and moderate speeds which correspond to most efficient climb, and undoubtedly accounts for the difficulty which has usually been experienced in computing rate of climb. It is well known that, although the maximum horizontal speed of a new machine can be predicted with a high degree of accuracy from performance computations of the ordinary type or from a wind-tunnel test of a model, an attempt to predict climbing speed in a similar fashion very commonly gives a value distinctly higher than that found in a free-flight test of the completed machine.

EFFECT OF SLIP-STREAM ON PERFORMANCE.

The method of applying the slip-stream correction to the parasite resistance of the parts inside the slip-stream area to secure the corrected total resistance and the horsepower required for flight is simple and obvious, differing in no essential particular from that employed when the correction factor is assumed to remain constant.

We have been considering so far a case in which the engine speed is assumed to remain constant at all speeds of flight, a case which is never exactly realized. If the throttle be kept open, the load on the engine will be greatest, and the revolutions per minute will consequently

be lowest, when the slip percentage is greatest; or, in other words, when the speed of flight is lowest, and the engine speed with open throttle may be 5 per cent or more lower when the plane is climbing at an angle of attack of about 8° than when it is flying level at an angle of attack in the neighborhood of −1°. The variation of revolutions per minute is small, however, and we shall not go far astray if we stick to our original assumption that the engine speed remains constant so long as the throttle is wide open. We have now to consider the effects of partially throttling the engine, and the modifications of slip-stream effect which are involved. When the throttle is partially closed the engine speed is reduced and the value of V/ND, the propeller slip function, is therefore increased. It is evident from Fig. 1 that an increase in V/ND causes a decrease in the ratio of V_s to V. If the engine be throttled to half its original number of revolutions, for example, maintaining the same speed of flight and varying the slope of the flight-path, the value of $(V/ND)/(V/ND)'$ will be doubled and the ratio of V_s to V will be reduced, for a machine flying at 40 per cent of the speed for which the propeller was designed, from about 2.6 to 1.4. The parasite resistance of parts in the slip-stream would then be reduced by 71 per cent by throttling the engine, although the speed of flight would remain the same. This, of course, is an extreme case, as the engine speed in level flight would seldom drop to less than 75 per cent of the rated speed. If the plane is gliding with the engine cut off, the slip-stream effect will of course disappear entirely.

It is of interest now to examine the variation of the slip function and of the slip-stream correction when the machine flies at different speeds in the neighborhood of the maximum attainable, the engine always being throttled just sufficiently to keep the flight-path horizontal. When the plane is flying at high speed the angle of attack is small and the coefficient of wing drag is near its minimum value. This coefficient D_o will therefore remain almost constant if the angle is varied slightly, and the total wing drag will be very nearly proportional to the square of the speed for small changes in speed in the neighborhood of the maximum attainable. The parasite resistance is always proportional to the square of the speed, neglecting the small effect of inclination of the body, struts, etc., and the total resistance will therefore be proportional to the square, and the horsepower required to the cube, of the speed of flight, provided that the slip-stream correction factor remains constant. This relation, it must be remembered, holds only in the neighborhood of the maximum speed of flight (say for angles of attack between −2° and +3°). It can be shown that, if we assume the validity of the blade element theory of propeller design, the power absorbed by a given propeller is proportional to V^3 if the slip function be kept constant. Since the horsepower absorbed must vary as V in order that it may be equal to the horsepower required for level flight, it is evident that the slip function will be approximately constant so long as the machine flies in a horizontal path at an angle close to that of minimum drag. To take a concrete illustration, if the speed of flight be decreased 10 per cent the maximum power required for flight will decrease to $(.9)^3$, or 73 per cent of the original value. In order that the slip function may remain constant the engine speed must be decreased by 10 per cent. Since the value of V/ND is unchanged, the ratio of slip-stream velocity to speed of flight will also remain unchanged, so long as the flight-path is horizontal and the speed is fairly high. At very low speeds the slip-stream correction factor in horizontal flight is larger than at those in the neighborhood of the maximum, as the revolutions per minute decrease less rapidly than the flight speed, and the slip function consequently decreases at low speeds.

DEDUCTIONS FROM THE MOMENTUM THEORY OF PROPULSION.

Our deductions to date have all been based, owing to an unfortunate paucity of experimental data, on a single set of tests in which only one propeller was used. It is now of interest to examine the question from another point of view, and see what we can learn by the application of pure theory.

The Rankine-Froude theory of fluid propulsion is based on the assumption that the thrust given by a propeller is equal to the sternward momentum imparted to the fluid in unit time.

If we assume the correctness of this theory, and further assume, as we have already done, that the slip-stream has a diameter equal to 0.9 of the propeller diameter and that the velocity of the air is uniform all over the slip-stream, we can readily compute the slip-stream velocity, given the engine horsepower, propeller efficiency, propeller diameter, and speed of flight.

Let P = horsepower.
T = propeller thrust.
η = propeller efficiency.
D = propeller diameter (feet).
V = speed of flight (feet per second).
V_s = slip-stream velocity (feet per second).

A_s = area of slip-stream = $.81\frac{\pi}{4}D^2 = .636\ D^2$.

ρ = density of air = .07608 pounds per cubic foot under standard conditions.

M = mass of air passing through propeller in 1 second = $\frac{\rho}{g} \times V_s \times A$.

$$P = \frac{T \times V}{550 \times \eta}$$

$$T = \frac{550 \times P \times \eta}{V} \tag{1}$$

From the momentum theory of fluid propulsion,

$$T = M \times (V_s - V) = \frac{\rho}{g} \times A_s \times V_s \times (V_s - V) = .0015\ D^2 \times V_s \times (V_s - V) \tag{2}$$

Equating (1) and (2),

$$\frac{550 \times P \times \eta}{V} = .0015\ D^2 \times V_s \times (V_s - V)$$

$$(V_s - V) \times V_s = \frac{367{,}000 \times P \times \eta}{V \times D^2}$$

It is a well-known fact that, for any given value of the slip function, V/ND, the power consumed in driving a propeller of any particular type is proportional to V^3D^2. We can then write $K_1 V^3 D^2$ in place of P in the above equation.

$$(V_s - V) \times V_s = 367{,}000\ K_1\ V^2 \eta$$

Dividing through by V^2

$$\left(\frac{V_s}{V} - 1\right) \times \frac{V_s}{V} = 367{,}000\ K_1 \times \eta$$

and solving:

$$\frac{V_s}{V} = \frac{1}{2}\left(1 + \sqrt{1 + 1{,}468{,}000\ K_1 \eta}\right) \tag{3}$$

It is evident that any change in propeller design, such as an increase in the number of blades which tends to increase the power absorbed by a propeller of given diameter, will increase the magnitude of the slip-stream correction as given by this formula.

It is of considerable interest to compare the slip-stream correction obtained by this theoretical analysis with that found by actual measurement of the air velocities behind a propeller. This has been done for Eiffel's propeller No. 9, the experimental data for which we have already studied. A table of K_1, η, and the theoretical slip-stream correction for various values of V/ND is given below, and figure 2 shows the comparison between the theoretical and experimental values of V_s/V.

V/ND	$K_1 \times 10^6$	η	V_s/V
0.347	6.02	0.590	1.745
.433	2.91	.672	1.484
.503	1.73	.725	1.341
.540	1.35	.742	1.285
.614	.76	.750	1.178
.694	.52	.710	1.120
.754	.31	.640	1.067
.812	.17	.390	1.024
.857	.14	.048	1.002

The coincidence between the two curves in figure 2 is quite extraordinary, especially in the neighborhood of the point of best propeller efficiency. At no point in the range corresponding to conditions of normal flight do the two values disagree by more than 2 per cent. This exactitude of agreement must, however, be regarded as largely fortuitous, as Eiffel's experiments themselves could hardly be accurate to such a degree.

The slope of the theoretical curve is a little less than that of the experimental one, but even this slight discrepancy can be accounted for by our failure to take account of the variations in diameter of the slip stream, which, as we have already seen, varies somewhat in size with changing speed of flight.

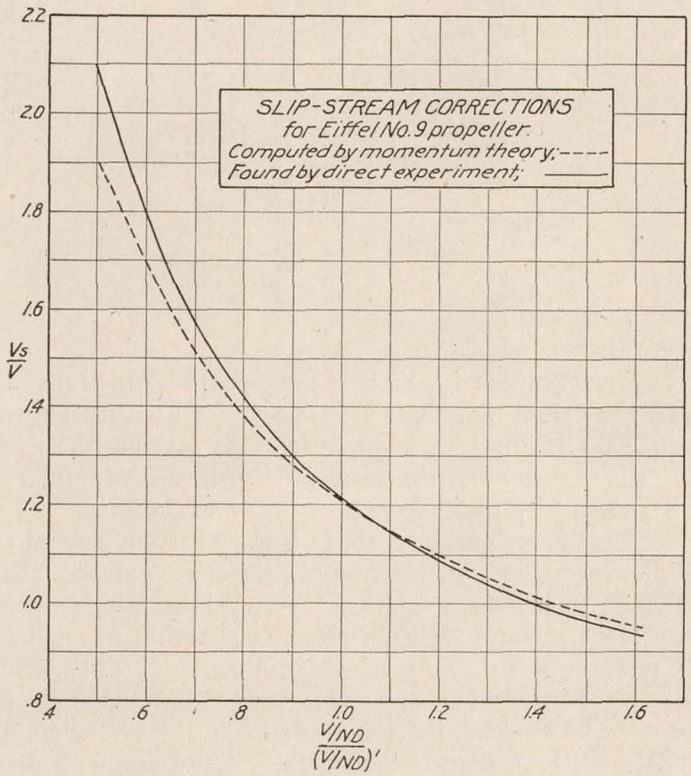


FIG. 2.

It appears that the formula (3) can be used without hesitation to secure the slip-stream correction and the correction can undoubtedly be determined with much greater accuracy in this way than by any adaptation of the results of experiments on propellers of type differing from that which is to be employed. K_1 can always be determined for any machine when the speed of flight, propeller diameter, and horsepower delivered by the engine under any given conditions are known. The efficiency can be computed from the propeller drawings by the standard blade element method. The application of (3) is, however, somewhat more tedious than is the simple process of reading the slip-stream correction from the curve of figure 1, and the choice between the two methods, where the propeller is close to the usual form, is largely a matter of personal preference, with the computation by the momentum theory having the advantage in respect to accuracy.

In order to check the validity of our original assumption that the slip-stream correction factors at the point of maximum efficiency is the same for all propellers, the values of this factor have been computed, by formula (3), for all the propellers tested by Eiffel up to 1914, and also for some of those tested by Dr. Durand.[1] The values of the correction for the various propellers are tabulated below:

Eiffel.

No.	V_s/V
1	1.354
2	1.245
3	1.122
4	1.161
5	1.435
6	1.361
7	1.235
8	1.170
9	1.178
10	1.155
11	1.165
12	1.140
13	1.241
14	1.268
15	1.219
15a	1.258
16	1.373
17	1.373
18	1.439
19	1.095
20	1.065
21	1.159
22	1.339
23	1.170
24	1.108
25	1.166
26	1.233

Durand.

No.	V_s/V
1	1.169
2	1.178
3	1.126
4	1.145
5	1.199
6	1.245
7	1.205
8	1.241
9	1.285
10	1.330
11	1.330
12	1.329
13	1.151
17	1.222
21	1.296
25	1.183
29	1.271
33	1.390

The variation in V_s/V is greater than might have been expected, Eiffel's 27 propellers, showing values ranging from 1.065 to 1.439. Just above half of the models tested have values between 1.15 and 1.35, and we can safely say that these will be the limiting values for two-bladed propellers of normal type and pitch. In the case of the Durand propellers, V_s/V lay between 1.15 and 1.35 for all except 2 of the 18 examined.

The figures obtained above lead to certain general conclusions as to the dependence of the slip-stream effect on the type of propeller employed. It appears that V_s/V depends primarily on pitch, being high for those propellers in which the pitch-diameter ratio is least. Eiffel's No. 1, for example, which shows a very high V_s/V, had a pitch of only about one-half the diameter, whereas No. 20, for which V_s/V was only 1.065, had a pitch of 1.4 times the diameter. It appears, furthermore, and rather surprisingly, that the slip-stream effect is substantially independent of blade width and blade form, the propellers with blades of constant width showing, on the whole, a slightly higher V_s/V than those with more rounded blade tips.

The use of a cambered face on the blades increases V_s/V. Durand Nos. 5 and 29, for example, are exactly alike except that the former has a flat, the latter a cambered, blade face, and No. 29 gives a considerably higher slip-stream velocity than does No. 5. The most pronounced effect, however, comes from varying the number of blades. Eiffel's Nos. 15 and 16 are exactly similar except that the former has two blades, the latter four (Nos. 17 and 18 are also four-bladed), yet the first gives a velocity ratio of 1.22, the second of 1.37. It is customary, in using the Drzewiecki, or blade element, theory of propeller design, to assume that two narrow blades are exactly the same as one wide one, but analysis of experiments makes it appear that that assumption is far from the truth, and that a given blade area will absorb more power when it is subdivided among several blades than when it is concentrated in two.

[1] Third Annual Report of National Advisory Committee for Aeronautics; Washington, 1918.

REPORT No. 72

WIND TUNNEL BALANCES

BY

EDWARD P. WARNER and F. H. NORTON
Aerodynamical Laboratory, National Advisory Committee
for Aeronautics, Langley Field, Va.

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REPORT No. 72.

PART 1.

WIND TUNNEL BALANCES.

By Edward P. Warner and F. H. Norton.

DESCRIPTION AND DISCUSSION OF THE BALANCE FOR THE ADVISORY COMMITTEE'S WIND TUNNEL AT LANGLEY FIELD.

In designing a balance for the Langley Field wind tunnel, after careful consideration and analysis of the various types which have been used at other laboratories, as well as of several arrangements not hitherto tried which were suggested, it was decided to adhere in general to the type of balance which has been used, substantially without change, for a number of years by the National Physical Laboratory. There is no other so simple to use, yet the accuracy attainable is as great as with any of the more complicated types. The design was modified in some respects to permit of the measurement of larger forces than those for which the original N. P. L. balances are suited, as well as to introduce certain changes which seemed likely to improve the convenience or accuracy of the work. In the description which follows particular attention will be paid to the details in which the balance differs from its prototype, very full descriptions of the latter having been printed in many places.[1] For the benefit of those who are not familiar with the N. P. L. balance it may be briefly explained that its distinguishing feature is the carrying of the whole balance on a single pivot, thus permitting it to rock in two planes. The model is mounted above the pivot with its Y axis vertical (i. e., "standing on the wing tip") and the lift and drag are measured simultaneously by hanging weights on two arms at right angles to each other and balancing the apparatus up in two planes at once. The leverage ratio in this balance, as in those in the N. P. L. 4-foot tunnels, is one-half, the distance from the main pivot to the center of the model being 137 cm. (54 inches), while that from the pivot to the scale-pan sockets at the ends of the weighing arms is 68.5 cm. (27 inches).

Assemblies and sections of the balance are given in Plates I–IV, and photographs of the completed instrument in Figs. 1 and 2. Figs. 3 to 10, inclusive, illustrate all the parts (except about 10 specially made parts and such stock hardware as machine screws and nuts) entering into the construction of the balance. Each part is numbered in these illustrations, and frequent reference will be made to them in discussing the working of various elements.

RIGID PARTS.

The frame is essentially the same as in the original N. P. L. balance, except that it is cast in one piece instead of having the head which carries the moving part of the instrument cast separate and bolted on. Furthermore, where the British design has only one member projecting from the frame head the Langley Field balance has three, one passing into the movable portion of the balance and carrying the socket for the main pivot, the other two passing around the outside of the movable portion and a little more than half encircling it. A cast-iron yoke is bolted to the ends of these encircling members, and the balance proper is then entirely surrounded by a ring, with just enough clearance to permit it to rock without danger of striking the frame.

[1] Report of British Advisory Committee for Aeronautics, 1912–13, pp. 61–66: London.

The object of thus encircling the balance with the frame was to provide a point of attachment for the guide arms. In the N. P. L. instrument they pass through holes cut in the sides of the moving portion and are bolted directly to the single frame lug which carries the main pivot socket. Since the Langley Field balance was designed to carry loads up to 20 kg. on the model some stronger method of attachment for the guide arms was required, as well as one which would permit of easier assembling and dismounting.

The guide arms are made of steel tubes, 25.4 mm. (1 inch) in outside diameter and with 5-mm. walls. They are pinned into sockets at the end, and these sockets are bolted directly to the frame or (in the case of the lift arm) to the yoke which connects to the frame and passes around the balance. The worst stress in the guide arms occurs when there is no weight on the weighing arms and the load on the model is at a maximum or when the wind is suddenly stopped with the weight in the scale-pans adjusted to balance a large load. With a load of 20 kg. acting on the model the force applied at the end of the guide arm is 40 kg., and the bending stress at the root of the arm is 1,475 kg. per square centimeter (21,000 pounds per square inch). The guide arms carry cages which slide in dovetailed slots and can be adjusted by screws through a vertical range of about 6 mm. in order to facilitate the preliminary lining up of the instrument with the lower pivot engaged. Instead of using a thread or wire as a reference line a piece of glass with a hair line scribed on it is mounted in the side of each cage. The weighing arms are nickel plated, and the reference line carried by the cage is lined up with its own reflection in the weighing arm and with a similar line scribed on that arm, thus avoiding any possibility of parallax due to the considerable distance between the two arms.

The dashpot is nearly identical with that on the N. P. L. instrument. It was cast with two passages, connecting opposite pairs of chambers, cored in the bottom, and a petcock communicates with each of those cored passages. This insures that the damping liquid will always stand at the same level in opposite chambers, but it is still possible to have it at different levels in adjacent chambers or to use liquids of different vicosities if it is desired to damp the oscillations in one plane more powerfully than those in the other.

BRAKE AND LOWER PIVOT SOCKET.

The brake, a short distance above the dashpot, is of a different type from that used by the N. P. L. as it was necessary to secure a very powerful grip, capable of resisting a large torsional moment, on the lower tube, but without risking crushing that thin-walled tube. The brake used is identical in principle with a lathe collet and gives a uniform pressure over virtually the entire circumference of the tube.

A mechanism for raising and lowering the lower pivot socket, causing engagement or release of the pivot, is mounted underneath the dashpot. The parts are illustrated and numbered in fig. 6. The handle 1 is fastened to the cam 4 and the rotation of this handle through a quarter turn raises the cam 3 by 10 mm. The adjusting screw 5 is screwed into 3 and transmits the vertical movement to the pivot socket 7 through the sleeve 6 and the spring 8; 7 rises freely until it comes in contact with the lower pivot, and thereafter, as 3 and the attached parts continue to rise, 8 is compressed, increasing the pressure between the pivot and its socket. When 3 has been raised to its maximum height the pressure between the pivot and socket can be adjusted by turning the screw 5 in the cam 3, two turns of the screw being sufficient to change the pressure from 0 to 20 kg. The spring 9, much weaker than 8, is used to assist gravity in throwing the socket out of engagement after the cam has been lowered. This device is very much quicker and easier to operate than the usual simple screw and spring, and it has the great advantage of permitting an adjustment of pressure for different lateral forces of the pivot against its socket and for different total weights to be carried. The load can thus be distributed between the upper and lower pivots in any manner desired.

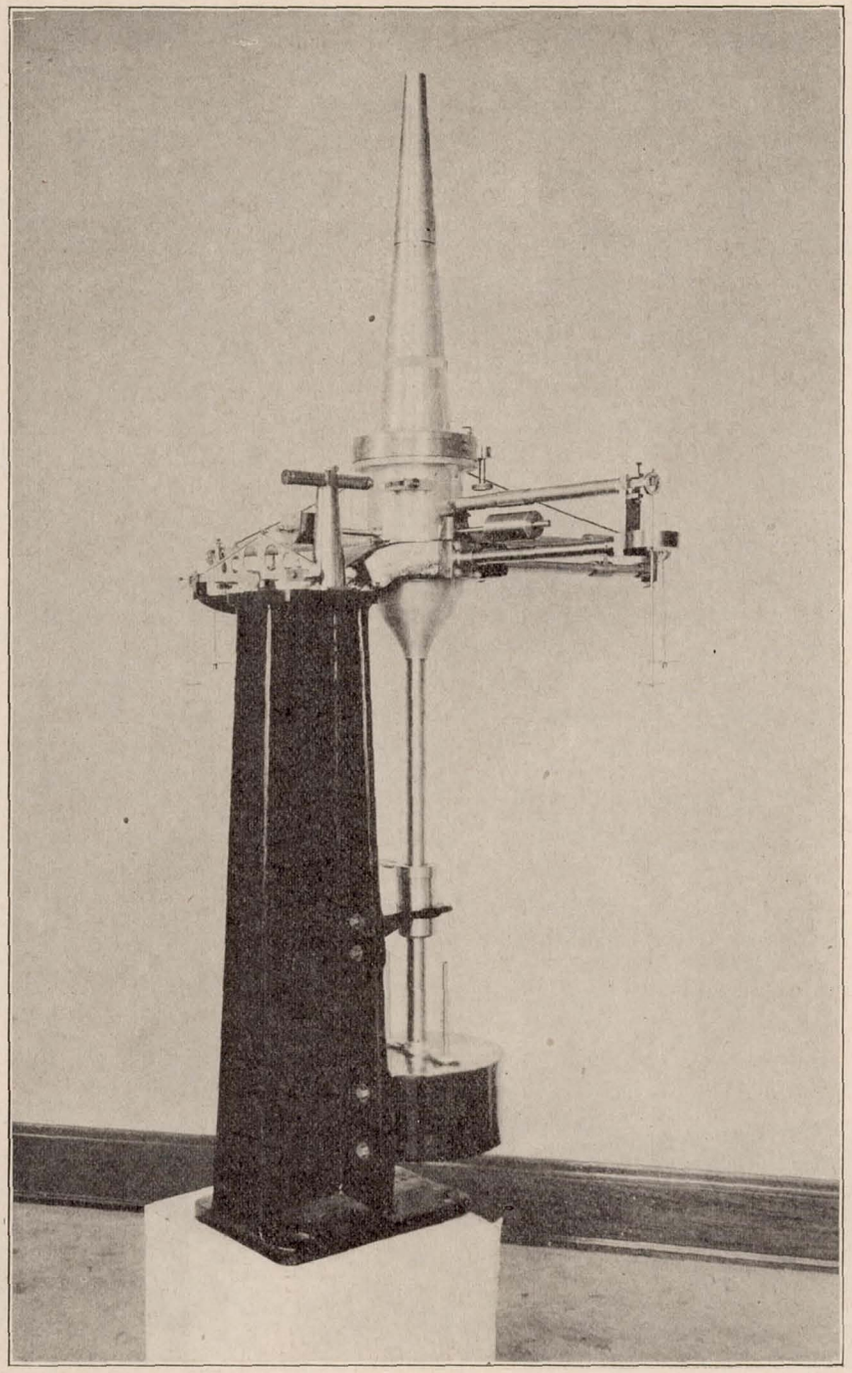


FIG. 1.

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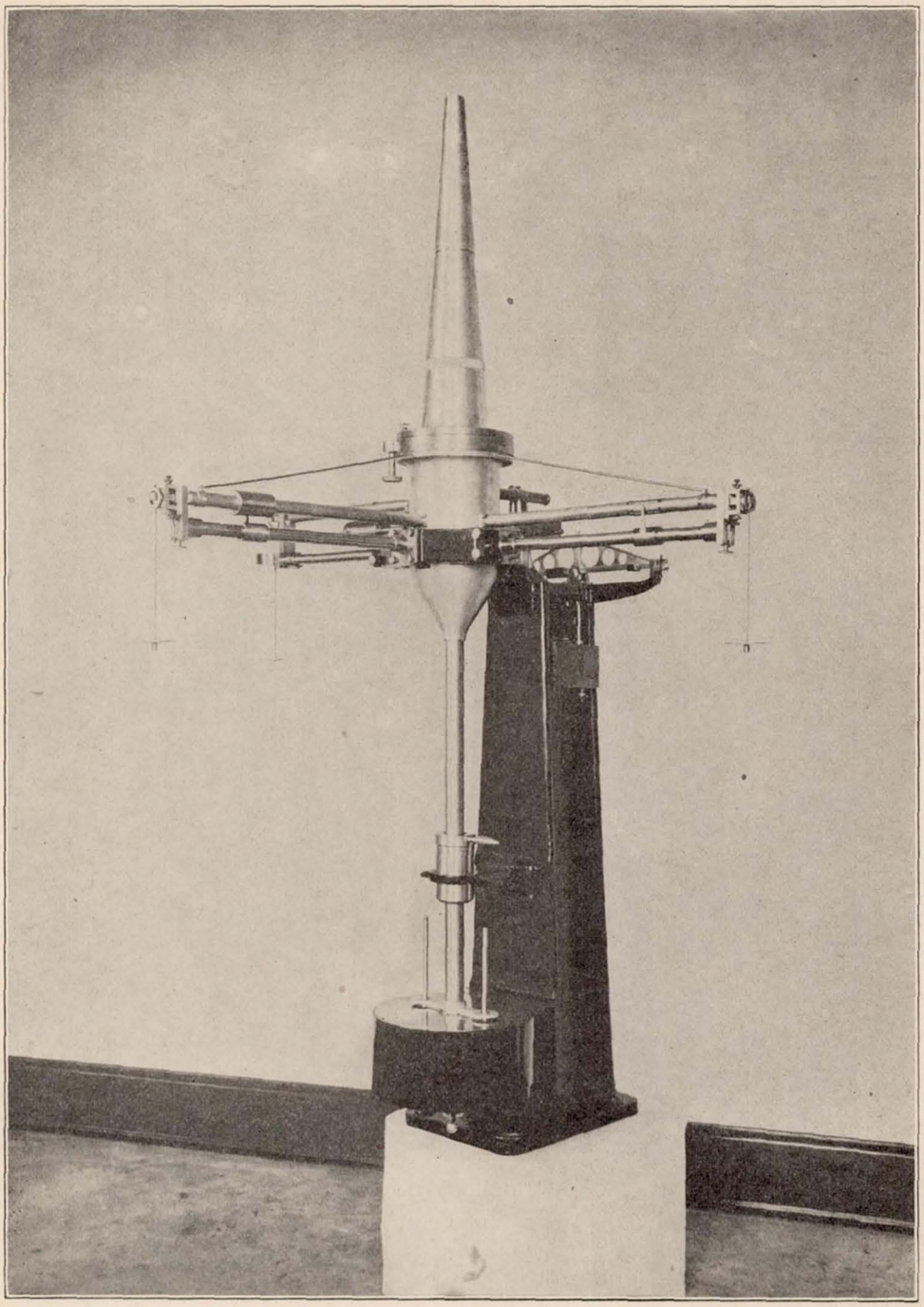


FIG. 2.

MOVING PARTS OF BALANCE.

In order to reduce the weight of the main pivot, the upper and lower parts of the balance were both cast of aluminum alloy instead of bronze, as has been the practice hitherto. Since an aluminum to aluminum bearing at the point where the pieces touch would be undesirable, a steel plate is screwed to the lower face of the upper part. This plate has teeth cut around its periphery, and these mesh with the teeth on the pinion whose case is mounted on the clamping ring (to be described later). By rotating the pinion knob the upper part of the balance is turned with reference to the lower part and the angle of incidence can thus be adjusted very accurately. The main balance castings were proportioned for stiffness and for reasonable ease of construction, rather than from the standpoint of stress. The maximum bending stress in the lower head is 29 kg. per square centimeter, giving a factor of safety of about 40, and that in the upper head is quite as large.

The force acting on the balance, and tending to separate the upper and lower heads on one side while forcing them together on the other, is too great to permit the use of the T-slot arrangement employed by the N. P. L., and the two pieces were therefore clamped together by an alloy-steel ring threaded onto the lower part and with a flange turned inward and bearing against the upper portion. This ring is one of the few parts of the balance which is probably materially stronger and heavier than it needs to be. The stress in such a flange is difficult to compute with accuracy because of uncertainty as to the distribution of the pressure between the surfaces, but it is estimated on the best assumptions available, as 700 kg. per square centimeter (10,000 pounds per square inch), giving a factor of safety of over 10. It would be safe to reduce the maximum thickness of the clamping ring and its flange to 3 mm. (three-sixteenths inch), and the weight could thus be reduced by about 500 gms.

The clamping ring covers up the portion of the upper head which normally bears the graduated circle, and the graduations have therefore been transfered to the horizontal portion of that head, just inside the inner edge of the clamping ring flange. Since this is too high from the floor to be convenient for direct observation, a prism is mounted on the clamping ring so that the graduations can be read with the eye on a level with the plane dividing the two parts of the balance. A movable vernier is mounted at the same point and its graduations are also reflected in the prism.

The weighing-arms, instead of being cantilevers, as in previous balances of this type, are trussed with tie-rods. The arms are made of steel tubes 25.4 mm. (1 inch) in diameter, with walls 1.5 mm. (0.06 inch) thick, and are trussed with rods 4.5 mm. in diameter, making an angle of 12°.5 with the arms themselves. The compressive stress in the arms under the maximum load is 159 kg. per square centimeter (2,260 pounds per square inch) and the tensile stress in the tie-rods is 943 kg. per square centimeter (13,400 pounds per square inch). In order to carry the same load with solid arms acting as cantilevers they would have to be 24 mm. in diameter, or approximately the same as the outside diameter of the thin-walled tubes now used. The deflection with cantilever arms would be much greater than with trussed, and the weight would be at least twice as great as the weight of the present arrangement.

Counterweights are provided for lift and drag. The lift counterweight is made flat on top so that more weight can be easily attached there when large negative lifts have to be measured, by removing part of the weight placed in the scalepan to balance the counterweight. Since negative drags never occur, the same necessity of adding weight does not arise for the drag counterweight.

The main pivot is carried in a ribbed plate cast of aluminum alloy and fixed inside the lower part of the balance. This plate carries, in addition to the main pivot, two pivots and two knife-edges, arranged around the circumference of a circle. All five pivots and knife-edges lie on the same level. The balance frame carries, in addition to the main pivot socket, a pivot socket and a knife-edge socket in line with the lift arm and a little lower than the main socket. When it is desired to measure drag alone the main pivot is lowered with a special wrench inserted through a slot cut in the slide of the balance, and the balance is dropped until one of the

secondary pivots and one of the knife-edges mentioned above come into contact with their sockets, just as in the original N. P. L. instrument. The balance then has only 1 degree of freedom and the lift arm can be disregarded entirely unless the lift is very large, in which case enough weight should be hung on the lift arm to balance the lift approximately (within 1 or 2 kg.). If this is not done the weight of the balance may be insufficient to hold it down, and the pivot may rise from its socket entirely. The other pivot and knife-edge are used to measure lift alone. Their sockets are carried by a horseshoe-shaped link, pivoted to the frame at its open end and resting at the other end against the point of a screw which is threaded into the frame. This pair of sockets are in line with the drag arm and are normally a little lower than the pair used for measuring drag alone. When it is desired to measure lift alone, the screw supporting the closed end of the link is turned, raising the link and its pair of sockets until the sockets come in contact with the pivot and knife-edge and lift the balance off of the main pivot. The balance is therefore a little above its normal position when lift alone is being measured and a little below it when it is the drag that is taken, but the total vertical displacement does not exceed 2 mm.

The four dashpot fins and the platform on which the "sensitivity weights" rest are made of a single aluminum casting in order to get the weights as far as possible below the center of gravity.

The drawings and photographs show the balance only as far as the upper end of the trumpet top. Beyond this comes the spindle, which presents a special problem in that not only the weight and strength, but the outside diameter, must be taken into consideration, as the interference of the spindle with the flow about the wing is always a serious factor, and no effort must be spared to reduce it. It is very desirable that the wing be supported by the tip, as the interference of a center support is much greater. With a spindle attached at the wing-tip, the whole force on the model acts at a large moment arm to produce bending stress in the spindle. With a wing 60 by 10 cm. and a force of 20 kg., a spindle of mild steel has to be at least 16 mm. in diameter at the point of attachment to the wing to give a factor of safety of 4. With a spindle of high-grade heat-treated alloy steel this diameter can be reduced to 12 mm. For uniform stress, the spindle diameter at the trumpet top would be only 21 per cent greater than that at the wing, but it is well to taper a little more abruptly than this in order to secure increased stiffness. When the parasite resistance of bodies, airship hulls, or other streamline forms is being determined a very much smaller spindle can be used than when wings are being tested. With an airship hull of low resistance coefficient, the model being 12 cm. in diameter and being tested at a speed of 50 meters per second, the spindle diameter at the point of attachment need be only 1.9 mm. in diameter, tapering to 2.8 mm. at a distance of 15 mm. Here again a sharper taper would be advisable to reduce the deflection and avoid vibration of the model. In any case, however, a correction for the effect of spindle deflection (discussed in another section of this report) would be necessary with a spindle of such a small tip diameter as this.

PITCHING MOMENT DEVICE.

The torsion wire used by the N. P. L. for measuring pitching moments being unsatisfactory in some respects a secondary balance beam for weighing these moments directly is incorporated in the Langley Field instrument, as in that at the Bureau of Standards and several others. The moment weighing arm is an aluminum casting. The moment is transmitted to it from the lift counterweight arm of the balance through a strut and spring clamp similar to those used by the N. P. L. for preventing rotation of the balance, and is balanced by weight hung at the end of the horizontal beam of the weighing arm. The ratio between the lengths of the horizontal and vertical arms is 3, so that the weight in the scalepan is one-third the lateral pressure of the strut or clamp against the socket at the top of the weighing beam. If the lateral pressure becomes greater than the total weight of the beam and parts attached to it the knife-edges on which the beam rocks will jump out of their sockets, the sides of which have a slope of 45°. When tests are made at high speeds and with models so mounted that the pitching

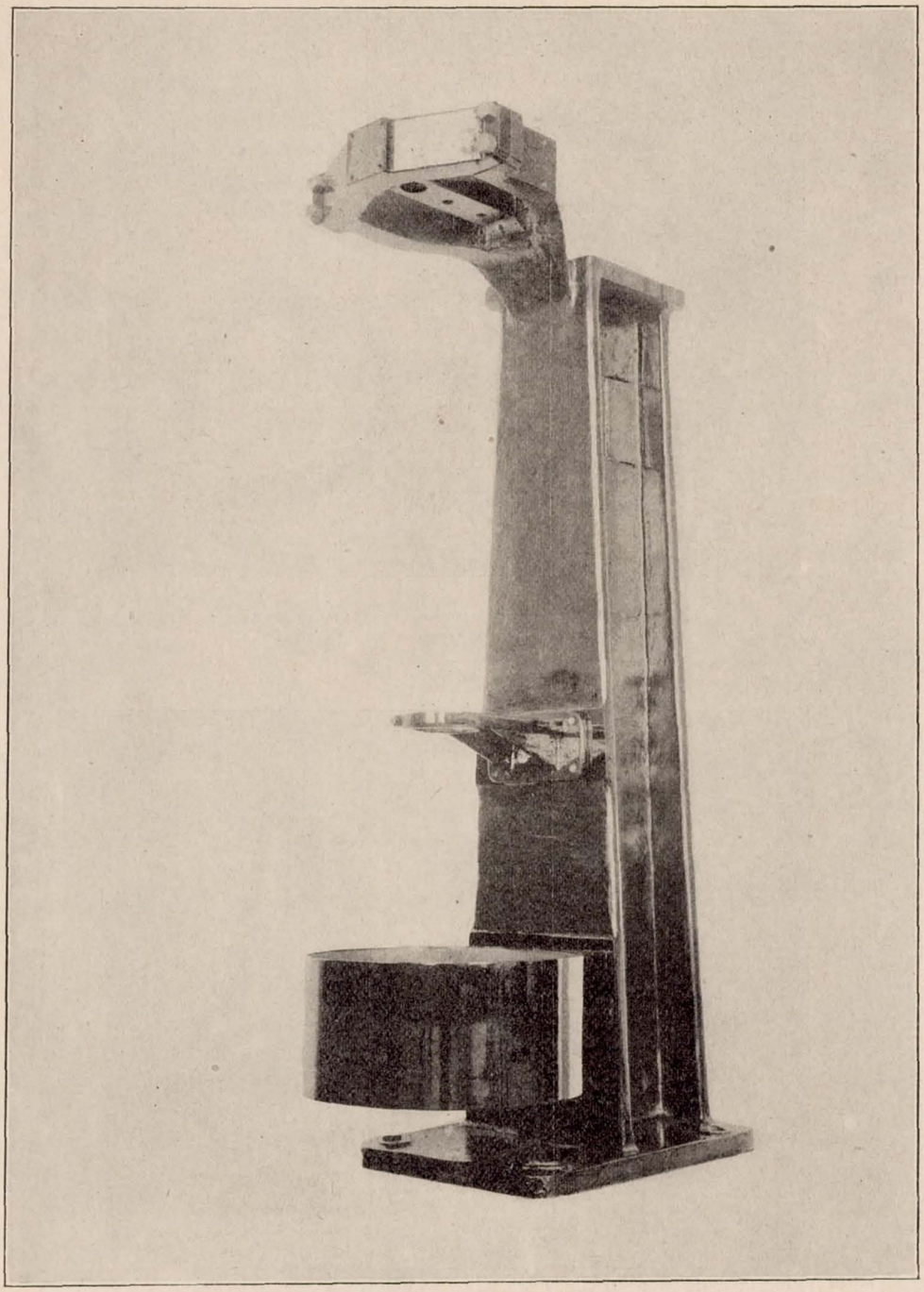


FIG. 3.—FRAME, DASHPOT, AND OTHER RIGID PARTS.

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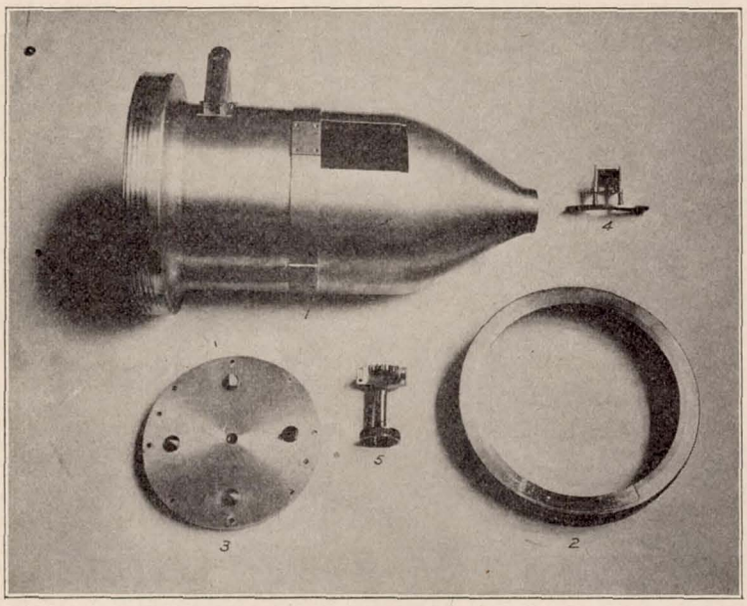


FIG. 4.—1, LOWER HEAD; 2, CLAMPING RING; 3, PIVOT PLATE; 4, VERNIER AND PRISM; 5, PINION AND CASING.

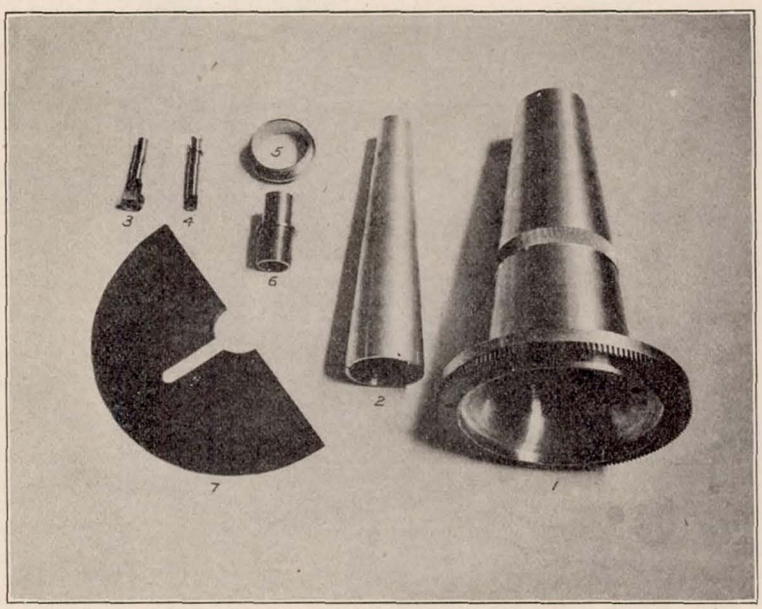


FIG. 5.—1, UPPER HEAD; 2, TRUMPET TOP; 3, 4, PIVOT AND KNIFE-EDGE SOCKETS; 5, 6, BUSHINGS; 7, DASHPOT COVER.

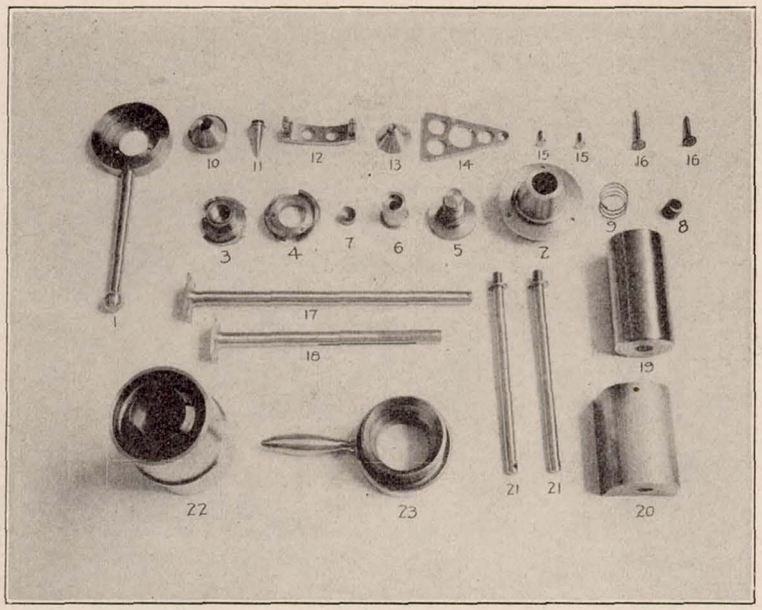


FIG. 6.—1 TO 11, LOWER PIVOT AND LOWER PIVOT SOCKET PARTS; 12, V. F. LINK FRAME; 13, V. F. ROD SOCKET; 14, V. F. LINK; 17, 18, COUNTERWEIGHT ARMS; 19, 20, COUNTERWEIGHTS; 21, SENSITIVITY WEIGHT SPINDLES; 22, 23, BRAKE PARTS.

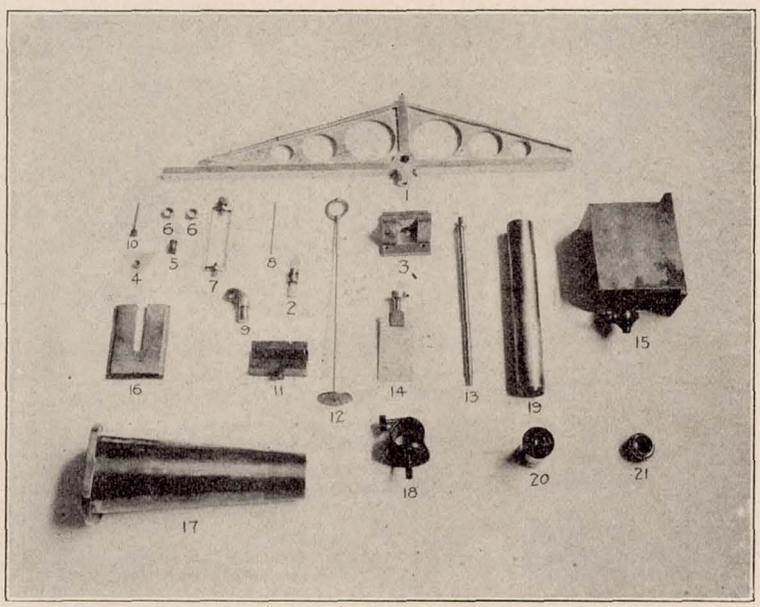


FIG. 7.—1 TO 16, MOMENT DEVICE PARTS; 17 TO 21, MICROSCOPE PARTS.

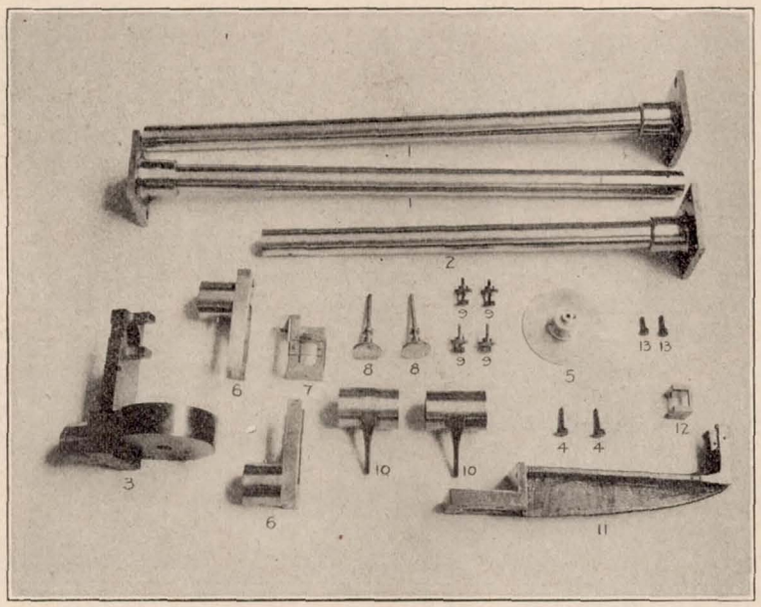


FIG. 8.—1, 2, GUIDE ARMS; 3, V. F. CAGE AND DASHPOT; 5, V. F. DAMPING VANE; 6, 7, CAGE CARRIER AND CAGE; 10, RIDER PUSHERS; 11, 12, MOMENT GUIDE ARM AND CAGE.

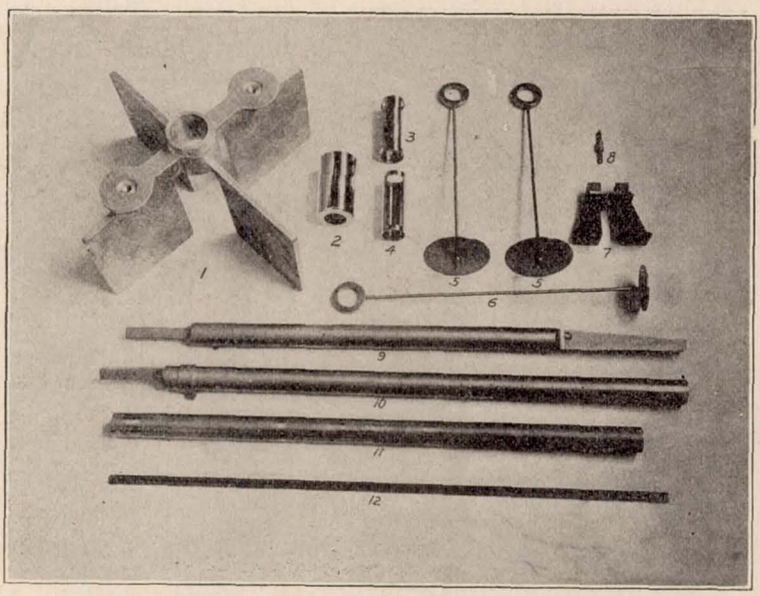


FIG. 9.—1, DASHPOT FINS; 2, 3, 4, RIDERS; 5, 6, SCALE PANS; 7, V. F. KNIFE-EDGE FRAME; 9, 10, 11, WEIGHING ARMS; 12, WEIGHING ARM TIE-RODS.

moment is large it is therefore necessary to add dead weight to the weighing beam to hold it down. A counterweight is placed opposite the scalepan on which the weights to balance the moment are hung, and this counterweight is heavy enough and placed far enough from the axis of rotation of the beam so that the zero weight which must be placed in the scalepan to balance the beam with no wind on is greater than the largest diving moment which is likely to be measured. Both stalling and diving moments can thus be measured with a single scalepan.

The spring clamp used for transmitting the moment to the weighing beam is made with a single helical spring behind one pivot. The pressure of this spring can be adjusted by turning the knurled head of the clamp. A C-spring of the type used on earlier N. P. L. balances could not be made to give the requisite pressure and still be kept within reasonable limits of size. The strut which opposes the spring clamp is made of a steel tube, 3 mm. outside diameter, 1.5 mm. inside diameter, with hardened points mounted in its ends.

A separate dashpot is provided for damping the oscillations of the moment weighing arm. The damping fin is carried at the lower end of a rod which runs down through a slot in the table top of the balance frame.

When lift and drag are to be measured the moment beam is locked, in order to prevent rotation of the balance about a vertical axis, by passing a pin through holes drilled in the sides of the moment guide arm and in the weighing arm itself. The balance can be adjusted for alignment of the arms with the wind by moving the socket which is set in the lift counterweight arm and which is provided with a screw adjustment.

MICROSCOPE FOR ALIGNMENT.

In order to check the alignment of the arms with the wind, a microscope is mounted on the table top of the balance frame, and a reference line is carried on the balance itself, exactly as in the original instrument except for mechanical details. The reference line is made adjustable with a micrometer screw in order that it may be brought into line with the cross hair of the microscope when the alignment is first determined or whenever it is checked. The reference line, once located, is left fixed, and the two lines are thereafter brought into alignment, whenever they get out from any cause, by moving the strut-and-spring clamp socket as described in the last section. Ordinarily the lines should come into register whenever the locking pin is passed through the moment weighing arm without any adjustment.

VERTICAL FORCE ARM.

When lateral stability or control is to be investigated, requiring the measurement of six forces and moments instead of three, the model is set up with the Y-axis horizontal and the lift is measured directly on the vertical force arm, which runs in the opposite direction from the drag arm. The method used in the Advisory Committee's balance is identical with that devised and used by the N. P. L., and fully described in the Report of the British Advisory Committee for Aeronautics for 1912–13. Since the lift on a wind tunnel model at high speeds is greater than the weight of the model, enough weights are strung on the vertical rod which passes inside the balance to insure that the total weight on the inner end of the V. F. weighing arm will be greater than the maximum lift.

CONCLUSION.

While it is perhaps unwise to attempt to set a limit to future progress in any direction, it is not believed that the N. P. L. type of balance will prove applicable to tunnel sizes and wind speeds very much in excess of those at present realized. The load becomes too great for a single pivot, the errors due to deflection rapidly run up with the size of balance, and the handling of the weights becomes an arduous task with growing forces on the model. Even in the present balance 40 kg. must be lifted onto the scalepan to balance the maximum lift. If there is to be much further increase in the values of LV reached in model experiments, that increase probably must be accompanied by the adoption of a new type of weighing instrument.

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REPORT No. 72.

PART II.

SENSITIVITY OF WIND TUNNEL BALANCES OF THE N. P. L. TYPE.

The balances used in aerodynamic measurements, whatever may be their type, work under conditions radically different from those to which practically all other weighing machines are exposed in that the load acting on the balance is never steady, but varies with the greatest rapidity. In a chemical balance the action of gravity on the weights and on the substance to be weighed is absolutely unchanging, assuming an absence of chemical or physical action with the surrounding air, and the only variable forces are those due to the currents of air striking the balance. In a good balance even these are guarded against by the inclosure of the balance in a case, means being provided for manipulating the weights from outside.

When it is attempted to measure forces due to fluid velocity the whole problem of instrument design is much altered, for it becomes necessary to balance a fixed force, the pull of gravity on the weights, against a variable one, the pressure on the object being tested. It was with the object of eliminating this dissymmetry that Lanchester devised, a number of years ago, his aerodynamic balance in which the two forces balanced against each other varied in the same way. In this instrument, used chiefly for finding the skin friction of plates, the object to be tested was held at one end of a horizontal arm, the other end of which supported a small flat plate so oriented as to be normal to the wind. The horizontal arm was free to rotate about a vertical axis through its center. In use the apparatus was exposed to a rapidly moving current of air, and the area or position, or both, of the normal flat plate, were varied until the arm showed no tendency to rotate. The moments about the axis were then equal and, since the distance of each surface from the center of rotation could be measured and since the resistance of normal flat plates had already been determined with a fair degree of accuracy by other experimenters, using other methods, it was possible to solve for the unknown resistance. Once the arm on this instrument was balanced, it should show no tendency to rotate due to changes in wind velocity, provided the velocity at any given instant was the same at the two ends of the arm, as the resistance of each object was very nearly proportional to the square of the velocity, and the ratio of the resistances would be quite independent of wind speed. For this same reason, indeed, measurements of the wind speed were wholly unnecessary for the determination of the coefficients. A device similar in conception was used by Dines at about the same time for measuring resistances. In this case the surface tested was carried on a whirling arm, and the resistance was balanced against the centrifugal force on a weight connected to the surface through a bell crank. Here, again, no measurement of speed was required, as the resistance of the object tested and the centrifugal force on the weight were both proportional to the square of the angular velocity of the whirling arm. An arrangement for balancing the force on two surfaces against each other is also used in Mr. Orville Wright's balance.

Such devices as these, however great their ingenuity, are inevitably unsatisfactory in some respects. In the first type described, a preliminary determination of the resistance coefficient for a flat plate normal to the wind was required, and the accuracy of all subsequent experiments was limited by the accuracy of this preliminary determination. No absolute measurements of resistance were possible. In both cases the mechanical complications introduced by the shifting of a surface or of a bob weight were extreme.

In nearly all balances used in aerodynamical laboratories at the present time, then, to return to the original statement, fixed and variable forces are involved. No satisfactory means of automatically controlling the wind velocity in a tunnel has yet been devised, despite the considerable number of trials which have been made, and it is still necessary to depend on manual regulation. This involves a distinct time lag between the occurrence of a velocity fluctuation and its correction by the manipulation of the rheostat, so that, even with a highly skilled operator, the wind velocity may vary more than ½ per cent each way from the mean value, the period of the velocity oscillation being from 2 to 10 seconds. A variation of ½ per cent in the wind velocity implies, since the forces vary as the velocity squared, a variation of 1 per cent in the forces acting on the model. The magnitude and nature of this variation must be kept always in mind in designing the balance, and the instrument must be so arranged as to yield the most accurate results possible under the special conditions which it has to meet.

We shall examine first the sensitivity of the type of balance originated at the National Physical Laboratory and used in this country at the Massachusetts Institute of Technology, at the new tunnel of the Curtiss Engineering Corporation, and in the Advisory Committee's tunnel now under discussion, in which a single pivot is used for support and the balance has two degrees of freedom.

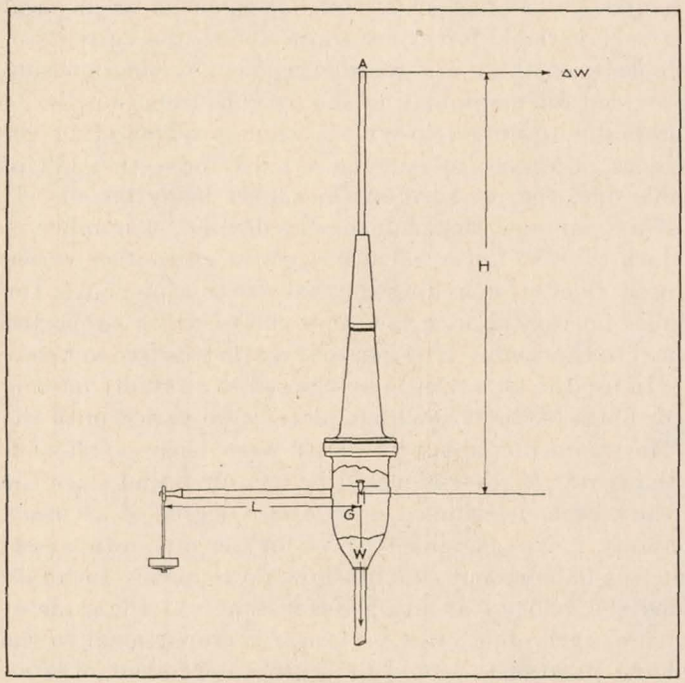


FIGURE 10.

In the first place, since it is necessary to balance up the instrument with no wind blowing in order to determine the amount of weight required to counterbalance the statical couple due to the model and the weight of the unsymmetrically disposed portions of the instrument, there must be a sufficient degree of "statical sensitivity," working as an ordinary physical balance, to keep the error in the readings on this preliminary test within reasonable bounds.

The magnitude of the error permissible depends upon the greatest absolute accuracy desired in the determination of lift or drag. In the case of a wing, this greatest accuracy is required in the measurement of the drag near those angles where the drag coefficient is a minimum. The minimum drag of a wing 60 by 10 cm. at a wind speed of 30 m. per second is about 72 g. In order that the error in the determination of this amount may not be over 1 per cent, the possible error in the preliminary run with no wind on should under no conditions exceed ½ per cent of the quantity to be measured, or, roughly, 0.35 g. In order that the measurement may be accurate to this amount it is necessary to make the theoretical sensitivity quite a little better than 0.35 g., as there is always some friction between a pivot and its socket, especially where, as in an instrument of this type, the pivot must be somewhat blunted in order that it may carry its load without crushing. In actual practice with heavy pivot-supported aerodynamic balances, it is found to be possible to secure a distinct movement of the drag arm due to changes of weight of 0.05 g. The lift arm is somewhat less sensitive, as motions of this arm are opposed not only by the friction between the pivot and its socket, but also by the friction between the lift counterweight arm and the two pivots (on the strut and spring clamp) which prevent rotation of the balance about a vertical axis. A sensitivity of 0.05 g., while it is sometimes useful when the forces to be measured are very small, as in the determination of the resistance of a streamline

body, is seldom required and seldom obtained. In general, if means be provided for adjusting the balance to give a sensitivity of 0.1 g., the results will be perfectly satisfactory.

The forces acting on the balance with no wind blowing are shown diagrammatically in figure 10. G is the combined center of gravity of the moving portions of the balance, the model, and the weights required to balance the unsymmetrically disposed portions of the model and of the instrument itself and is located at a distance $\times_0$ below the pivot. These weights are, of course, considered as applied at the point where the scalepan pivot touches its socket in the weighing arm. W is the sum of all these weights (balance, model, etc.). If a force Δw be applied at the point A or, what amounts to the same thing, if the weight on the scalepan be decreased by $k\Delta w$ where k is the multiplication ratio between the vertical and the horizontal arms of the balance, the balance will, neglecting friction, rotate about the pivot through an angle whose circular measure is equal to $\frac{h\Delta w}{Wx_0}$. The vertical movement of the reference line at the end of the weighing arm will then be $\frac{hl\Delta w}{Wx_0}$. If a certain value ϵ be assumed for the minimum perceptible value of this movement the sensitivity is given by the expression: $\Delta w = \frac{Wx_0\epsilon}{h \times l}$. An increase of sensitivity requires decrease of $\triangle w$, and this can be secured by modifying any one of four terms (it is assumed that ϵ can not be further decreased except by the use of a microscope for observing the movements of the reference line). W is always reduced to as low a value as possible if for no other reason than to keep down the load on the pivot, but there are well defined limits beyond which this reduction can not proceed without sacrificing the strength and stiffness of the instrument to an extent which will introduce large errors.

It would appear from the formula that $\triangle w$ could be reduced by increasing h or l, or both, but this is not actually the case, since any increase in these quantities requires more than a proportionate increase in weight in order to keep the deflection of the structure within safe limits. h is always made as small as possible without bringing the enlarged sections of the balance head close enough to the edge of the wind stream to interfere with the flow of air. l is made as short as has been found expedient (usually $l = \frac{1}{2}\ h$) as any shortening of l rapidly increases the amount of weight which must be handled and the load on the pivot. There remains, among the several variables, only x_0, and this can be reduced practically without limit. Here again the conditions under which wind tunnel balances work are peculiar. Whereas, in the ordinary scientific balance, it is necessary only to construct the beam and attached parts so that their combined center of gravity will be very slightly below the knife-edge and then to place the knife-edge sockets for the scalepans so that a straight line connecting them will pass through the knife-edge supporting the beam, thus making the sensitivity independent of the weight in the scale pans, in the case of the wind tunnel balance neither the total weight of the rigidly assembled moving parts nor the position of their center of gravity ever remains fixed for two consecutive tests (unless they be made on the same model under identical conditions). In the case of the Langley Field tunnel, for example, the weight of the model and of the spindle which supports it may lie anywhere between 50 and 10,000 g. Since the center of gravity of the model is about 140 cm. above the center of gravity of the rest of the balance, the effect of changing from the lightest to the heaviest model is to raise the center of gravity of the whole assembly by about 60 cm. Manifestly, if x_0 was very small with the light model in place, it would have a large negative value when the heavy one was substituted, and the balance would be unstable. On the other hand, if x_0 was adjusted for a small positive value with the heavy model its magnitude would greatly increase on changing over to the light one, Δw would therefore be augmented manyfold, and the sensitivity of the measurement would be much decreased just when the highest possible degree of accuracy would be required; that is, with a small model experiencing only small forces. It is therefore necessary to provide some means of adjusting the center of gravity when the weight of model is changed, and this is done by means of the "sensitivity weights" carried on the spindles just above the dash-pot (shown in the side view

in the general assembly drawings of the Advisory Committee's balance). When the weight of the model is large, a large amount of weight is placed on the spindles, about 70 cm. below the pivot, thus counteracting the tendency of the heavy model to raise the center of gravity. When there is no model in position a weight of about 800 g. is required on the spindles to balance the capsizing tendency of the balance itself, and an additional amount of about twice the weight of the model is required to maintain stable equilibrium with the model in place.

In the particular case of the committee's balance W, in the formula for sensitivity, is 20,700 g., not including the model, the weight in the scalepan, or any sensitivity weights except those required to balance the upsetting tendency of the balance itself. With a model in position and no wind on, the total weight supported on the pivot lies, in most cases, between 21,000 g. and 49,000 g., with an average value of about 28,000 g. h is 54 inches, or about 137 cm., and l is 27 inches, approximately 68.5 cm. ϵ may be taken as 0.2 mm. If the required sensitivity be taken as 0.1 g., which was shown above to be a fair average value, x_o must not be more than 1.7 cm. On the other hand, x_0 must not, under any conditions, be negative, as the balance will simply fall from side to side, never being in stable equilibrium, and it will be almost impossible to secure any readings whatever. Since a movement of 0.2 mm. at the end of the weighing arm corresponds to an angular rotation of 0.00029 radian, the product of the total weight and the distance from the pivot to the center of gravity may vary, without falling below the minimum permissible sensitivity, from 0 to 47,000 gm. cm. Since the sensitivity weights are located about 70 cm. below the pivot a variation of nearly 800 g. in the amount of weight used is possible without changing the sensitivity beyond the assigned limits. A somewhat closer adjustment than this is actually sought for, as it is not desirable, as will be shown later, to have too much sensitivity, but there is no necessity for changing the weights by smaller intervals than 200 g. Since the weight is always symmetrically disposed on the two spindles the smallest weight used is 100 g.

With the wind on the conditions are changed considerably. All the forces which acted during the preliminary run continue in operation, in addition to two new ones, the resultant force on the model due to the reaction of the moving air and the weight used to balance this resultant. (Lift and drag are here considered as a unit. Strictly speaking, of course, there are three forces acting—the resultant force due to the air, the pull of gravity on the lift weights, and the pull of gravity on the drag weights.) The moments of these two new forces about the balance pivot must be equal in order that the system may continue in equilibrium.

The conditions of stability of the system are also modified. The addition of weight to the scalepans has no effect, provided that the socket for the scalepan pivot is, as it should be, exactly in the horizontal plane through the main pivot when the balance is in equilibrium. Since there is inevitably some deflection of the weighing arms, no matter how well they may be braced, this condition can not be exactly obtained under all loads, but the deviation from the ideal is small. The magnitude of this deflection and the errors arising from it are examined in another part of the paper.

If the line of action of the force on the model intersects the vertical line through the pivot the change in moment arm due to small inclinations of the balance is negligible, and the moment of the force about the pivot remains substantially constant during the oscillations of the balance, so long as the force itself is not varied by fluctuations in the wind velocity or any other cause. If, however, the force does not act through a point vertically over the pivot the two forces supposed to be in equilibrium (that due to the pressure of the air on the model and that due to the pull of gravity on the added weights) will not continue in equilibrium when the balance inclines, and loss of sensitivity or loss of stability of the system will result, just as is the case when, in an ordinary physical balance, the line connecting the points of suspension of the scalepans passes below or above the knife-edges. It is rather difficult to define satisfactorily the point which, being analogous to the point of suspension of a scalepan, should be located directly above the pivot. For the present, at least, it will be simplest to consider separately the effects of each of the six forces and moments acting on an object, not necessarily symmetrical, exposed to a current of air.

Instead of considering the lift and drag, acting perpendicular and parallel to the relative wind, as is the ordinary practice in wind tunnel work, it will be best to deal with the forces resolved parallel to axes fixed in the model, in accordance with the current practice in stability work. In this way the moment arm of each force about the pivot will be fixed, whatever oscillatons the balance may undergo. The three forces are taken as acting at an origin which may be arbitrarily fixed, but which is almost always located at the center of gravity in the case of a model of a complete airplane and at the center of the leading edge in the case of an aerofoil.

Oscillations of the lift arm of the balance can obviously have no effect on the sensitivity. There only result is to incline the plane of the wings out of the vertical. This does not change the magnitudes of any of the forces along axes fixed in the model, nor of the moments about such axes, and, since the moment arms are constant, as pointed out above, the moments themselves will not change.

Oscillations of the drag arm, however, yaw the model instead of rolling it. As soon as the model yaws symmetry is destroyed and all of the forces and moments may be modified in some degree. The variations of the pitching moment are of no interest in the present connection, as the moment is exerted about a vertical axis, and can not possibly affect the equilibrium of the balance. Its only effect on the sensitivity is to change the pressure of the short balance arm against the strut which prevents the balance from rotating about a vertical axis, and so to change the friction at this point. Of the five quantities remaining, the variations in the forces Z and X, closely analogous to the lift and drag, are small, but not so small as to be negligible. In general, Z decreases slightly with small deviations from the position of symmetry, while X increases, but exceptions to both of these rules are sometimes encountered. The rate of decrease of Z is usually about one-half of 1 per cent for each degree of yaw. The change in X usually ranges from $\frac{1}{4}$ per cent to $1\frac{1}{2}$ per cent increase for each degree of yaw. Since the oscillations of the two arms of the balance are usually synchronous, both being governed by the variations in wind velocity, the effect of the movements of the drag arm, causing the model to take up an angle of yaw, on the lift must not be neglected. Since for a model of an airplane or other symmetrical object, the direction of change of X and Z is the same for a positive as for a negative angle of yaw, the effect of the changes is to assist a return to the position of equilibrium when the deviation is in one direction from that position and to oppose it when the deviation is in the other direction. If the initial sensitivity (with no wind on) is very great there is danger that this added moment opposing a return to equilibrium may be large enough to overcome the righting moment due to the weight of the balance. The result of this will be somewhat the same as the result of using insufficient counterweight to balance a heavy model, but the instability in this case will appear only for motions in one direction from the central position, and will usually lead to an underestimation of the lift and an exaggeration of the drag. To find the limitation thus placed on the maximum initial sensitivity the same method may be employed as that already used for finding the minimum permissible initial sensitivity. If the rate of change of longitudinal force be taken as 1 per cent per degree of yaw the upsetting moment due to a movement of the balance through the angle $\Delta\theta$ (circular measure) is $.57X \times \Delta\theta \times h$. For continued stability, this must be less than the righting moment due to gravity, $Wx_o\Delta\theta$. Equating the two, the condition of stability becomes

$$Wx_o = > 0.57Xh$$

It has already been shown that the initial sensitivity is given by the expression:

$$\Delta w = \frac{W \times X_o \times \epsilon}{h \times l}$$

In the case of the Langley Field balance, substituting $0.57Xh$ for Wx_o, and the values previously specified for l and ϵ, the limiting value of the sensitivity is found to be

$$\Delta w = \frac{0.57X \times \epsilon}{l}$$

$$\frac{w}{X} = \frac{0.57\epsilon}{l} = \frac{0.57 \times 0.02}{68.5} = 0.00015$$

The same method may be applied to the lift and leads to the conclusion that, with a model having a lift of 20 kg., the initial sensitivity must not be greater than 1.5 gms. This would be an extreme value of the lift, and it is seldom necessary to reduce the sensitivity below 0.5 gm. on account of the variation in lift, but, on the other hand, it is seldom that actual use could be made of the sensitivity of 0.1 gm., previously taken as the standard for which it was nesessary to provide Only on stream-line bodies, struts, and similar objects of small resistance would the possible accuracy of measurement be as great as this. It is in some respects a disadvantage of the N. P. L. type of balance that its "statical sensitivity" must be the same in respect of lift and drag.

Y, the third of the three forces acting on the model, is perpendicular to the plane of symmetry, and does not exist so long as the wind direction is parallel to that plane. As soon as the balance moves from its position of equilibrium, however. the model assumes an angle of yaw, and this gives rise to a force Y which is almost always negative for a positive angle of yaw and vice versa. The magnitude of Y for a given angle of yaw varies widely with the type of model and with conditions of test, generally being largest, relatively to the lift, at small angles of attack. The absolute values of Y are virtually independent of the angle of attack. For an angle of yaw of 1°, Y may be as high as 2 per cent of the lift for complete models at an angle of attack of 0°, or about 1 per cent of the lift at 4°. This force is largest when the wings have a considerable amount of dihedral or sweep back. In the case of fair-shaped objects, such as airplane bodies and airship envelopes, Y at an angle of yaw of 1° is usually from 10 per cent to 35 per cent of X. With models of the size used in the Langley Field wind tunnel, and with a wind speed of 50 m. per second, Y has a maximum value of about 50 gms. for bodies and 100 gms. for complete models.

If the origin of the reference axes is directly over the pivot when in equilibrium Y has no effect, as its line of action always passes through the pivot. If, however, as is usually the case, the model is set up with the origin forward of the vertical through the pivot Y will tend to produce instability in respect of the drag measurements, while not affecting the movements of the lift arm. If the origin is above (in the model, not in the tunnel; i. e., nearer to the upper wing than) the vertical through the pivot Y will tend to decrease the sensitivity in lift, assuming that the two arms oscillate synchronously, without affecting the measurements of drag. The opposite positions will, of course, have opposite effects. The magnitudes of these effects are very small. They would seldom modify the sensitivity by more than 0.02 gm., and they need not be taken into account, provided that the model is so supported that the origin is reasonably close to (within 8 cm., in the case of a tunnel 1.5 meters in diameter) the vertical through the main balance pivot.

There remain only the yawing and rolling moments to be considered. Both of these, denoted by N and L, respectively, make their appearance, like Y, as a result of the assumption of an angle of yaw, and do not exist while the wind direction is parallel to the plane of symmetry. The analysis of the action of these moments need not be followed through in detail. The first is unimportant, while the rolling moment, which may assume a considerable value in the case of a model or a wing with marked sweep back or dihedral, acts to increase the sensitivity in lift, and is therefore opposed to the effect of the change of lift itself for motions in one direction, while acting with it for motions in the opposite direction from the central position. The maximum value of the effect of the rolling moment is about 15 per cent of the maximum unstabilizing effect which may arise due to changes of the lift with angle of yaw.

It appears from this consideration of the various forces and moments and their variations that their effects on the sensitivity of the balance are usually very slight, but that they may become important, especially with regard to the lift measurements, for some models. Since the most important factors are the variation of the lift and drag, and since the magnitudes of these forces and the moment arms at which they act are quite independent of the location of the model with respect to the vertical through the pivot, this location has less effect on the sensitivity than might have been anticipated, although it is by no means a factor to be neglected. The position at which the spindle supporting the model is attached can be chosen, within fairly wide limits, from considerations of ease of attachment and of minimum interference with air flow about the model, rather than with any idea of modifying the effects of Y, L, and N.

The distribution of the effect on sensitivity of the three factors variable with position (Y, L, and N) depends on the location in the model of the arbitrarily chosen origin, and any one of these three can be made to have any desired effect by properly placing the origin. The total effect of the three, however, will manifestly be entirely independent of the position of that point.

There are certain types of balance in which the model moves always parallel to itself, and the forces accordingly are subject to no change during the oscillation of the instrument. These will be briefly discussed later.

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REPORT No. 72.

PART III.

POSSIBLE SOURCES OF ERROR IN BALANCES OF THE N. P. L. TYPE.

In order that some conception may be gained as to the relative accuracy necessary in the construction of the various parts of a balance, and as to the magnitudes of the errors which creep into the measurements from many sources, both those which are avoidable by careful construction and use and those which are inherent in the design of the instrument, these several sources of error will be taken up and analyzed separately.

(1) The first cause of errors in the determination of forces and moments, and one of the most important, is the deflection of the vertical portion of the balance under the force acting on the model. In measuring forces, since the portion of the balance below the main pivot is subjected to no transverse forces except the minute ones due to the resistance of the oil in the dashpot, all of the deflection takes place between the pivot and the model. In the case of a balance in which, as in that at Langley Field, the weighing arms are trussed by tie-rods, virtually all the deflection when the lower pivot is not engaged occurs above the point of attachment of these tie-rods. When pitching moments are being taken, however, the lower pivot is thrown into position to keep the balance axis vertical, and the deflection in the portion of the balance between the two pivots may be of considerable magnitude.

The error which deflection causes in the measurement of forces is due to the movement of the model and the upper portion of the balance with respect to the vertical through the main pivot. This movement changes the moment of the weight of the model about the pivot when the weighing arms are in the central position, and so changes the amount of weight required to keep the balance in equilibrium. Since the deflection is proportional to the load applied, and the error for a given weight of model is proportional to the deflection, the percentage error is quite independent of the load applied. It is necessary, then, in order to secure a definite percentage accuracy, that the balance and spindle be just as stiff and heavy for tests at 10 meters per second as for those at 50. Furthermore, since the balance, chuck, and spindle are circular in cross section at all points, the percentage error in lift due to deflection will be the same as that in respect of drag, except for the portion caused by the deflection of the model itself. The error here will be greater in lift than in drag at small angles of attack, as the model aerofoil bends much more readily about an axis parallel to the chord than about one perpendicular to the chord. At angles of 4° or more the resultant force is nearly perpendicular to the chord, and the difference just spoken of between lift and drag therefore does not appear. By far the largest part of the deflection error arises from the bending of the spindle which supports the model and which must have a small outside diameter in order that the interference with the flow of air may not be excessive. The deflection error always exists and is perfectly determinate in magnitude and sign, so that it can be computed or determined experimentally and correction made for it. This is sometimes done, but it is preferable to make the balance stiff enough so that no correction will be required.

In the quantitative discussion of deflection effects the English system of weights and measures will be used, as the constants of materials will be much more familiar in that system than in the metric to most readers. The deflection of the balance at Langley Field, from the pivot to the upper end of the trumpet top, a total length of 33 inches, is 0.00071 inch under a load of 1 pound, applied at the center of the tunnel, and the slope at the upper end of the trumpet top when the balance axis is vertical is 0.000099 per pound of load. With an aerofoil 60 by 10 cm. (approxi-

mately 24 by 4 inches), supported at its lower end by a spindle tapering in diameter from $\frac{9}{16}$ inch at the point of contact with the wing to 1 inch at the point where it enters the chuck, the total deflection, neglecting the bending of the aerofoil itself, is 0.0076 inch per pound. The deflection of an aluminum aerofoil, in respect of lift, may augment this by 0.0204 inch per pound, making a total of 0.0280 inch per pound with an aluminum model. The corresponding figure for a steel aerofoil is 0.0144 inch. There is also likely to be some permanent yielding at the joint between an aluminum aerofoil and its spindle, due to the softness of the aluminum. The remedy is to drill and cut a thread deeper into the model or to mortise the spindle into the wing and rivet them together.

The weight of an aluminum aerofoil of average thickness and 24 by 4 inches in plan form is from $1\frac{1}{2}$ to 2 pounds, and its center of gravity has just been shown to move 0.0280 inch under a lateral load of 1 pound perpendicular to the chord. (This is actually the distance that a point fixed in the plane of the chords of the aerofoil and halfway between the tips moves. The displacement of the center of gravity is a little greater, due to the bending of the wing, but the difference between the distance as just computed and that actually traveled is not very important.) The weight of the steel spindle is 1.26 pounds, and the distance moved by its center of gravity under a load of 1 pound is approximately 0.0015 inch. The total moment about the pivot due to these displacements with a 2-pound model is

$$(2\times 0.0280)+(1.26\times 0.0015)=0.0560+0.0019=0.0579 \text{ lbs. ins.}$$

This is equal to the moment given by a lateral force of 0.00107 pound applied 54 inches above the pivot. The error in the measurement of the forces on a model aerofoil caused by the deflections of balance, spindle, and model is then about 0.11 per cent. If the model aerofoil is made of steel instead of aluminum its weight is about 5 pounds, and the possible error in lift measurements is increased to 0.14 per cent despite the greater stiffness of the steel. It is evident that, both to keep down the deflection error and to reduce the weight resting on the pivot, aluminum is the material par excellence for models, and steel should only be used when it is desired to grind a standard wing to form with the highest possible degree of accuracy, or when the model is to be tested at so high a wind speed that an aluminum model would be likely to be stressed beyond its elastic limit. Even where accuracy of construction is the dominant consideration aluminum is but little inferior to steel, although the aluminum is, of course, much more liable to be bent or otherwise injured by careless handling. Brass, sometimes used for models in the past, is thrown quite out of consideration by its high density and low modulus of elasticity and stiffness.

The deflection of a complete model is somewhat less than that of a single wing under the same load, as the parts of the model tend to reenforce each other, even where the wing bracing is omitted. For a model weighing 10 pounds, a figure which should seldom if ever be exceeded with models of the size used in the Langley Field tunnel the error due to deflection should always be less than one-half per cent. This is large enough, so that some allowance for it would be required, but 10-pound models are fortunately the exception rather than the rule, and deflection effects can usually be ignored in the measurement of forces with this balance, although they have proved a very important factor with some balances of similar type.

The effect of deflection on the determination of pitching moments, and so of centers of pressure and vector diagrams, may become important with aerofoils of little stiffness tested at high speeds. Since moments are measured with reference to a vertical axis passing through the pivots, any deflection of the model support will shift the position of this axis in the model. This will result in the moments actually being measured with reference to a different axis from that experimentally determined before or after the run. Since all parts of the balance itself are circular in section the line of resultant deflection will be parallel to the line of action of the resultant force on the model. A shifting of the axis of moments parallel to the line of action of the resultant force manifestly does not affect the magnitudes of the moments, and the deflections of the balance proper can therefore have no effect on the determination of the location of the vectors. The model, however, does not, by any means possess radial symmetry and the di-

rection of its deflection is almost constant and independent of the direction of the force acting, since only the component of that force which is perpendicular to the chord of the aerofoil is effective in bending the model. Strictly speaking, the component of interest is that perpendicular to the principal axis of the section, not to the chord, but the two are nearly coincident. The principal axis have been determined for a number of sections, and the angle between the principal axes and the system of axes parallel and perpendicular to the chord was not, in any case, more than $1\frac{1}{2}°$. The deflection of the average aluminum model due to its own bending alone has been shown to be 0.0204 inch per pound, or 0.204 inch under a load of 10 pounds, which is the maximum that most aerofoils of cast aluminum alloy will safely sustain. The deflection under unit load is only one-third as much for a steel model as for an aluminum one, but the maximum load liable to be sustained is about four times as great, so that the maximum total deflection for a steel model is in the neighborhood of 0.27 inch. The angle between the vector of resultant force and the principal axis of maximum moment of inertia is never much more than 9° at any angle of incidence from 0° to 18°. The error in determination of the center of pressure or vector position would therefore not exceed two-thirteenths of the deflection of the model, and the largest error in that determination for an aluminum aerofoil subjected to a force of 10 pounds would not exceed 0.031 inch, or 0. 8 per cent of the chord. Over the most portant range of angles, that in which most normal flying is done, from 1° to 8°, the error would be less than half as large as this. In general, it may be said that it is necessary to make some allowance for the effect of model deflection on pitching moment when the test is run at a wind speed of 30 meters per second (approximately 66 miles per hour) or more with an aluminum, and at a speed of 50 meters per second or more in the case of a steel, model. Speeds above the latter figure are never reached in the course of ordinary testing, and, indeed, the former is seldom exceeded.

Although it has no direct effect on the accuracy of the measurements the deflection of the lower tube is of some interest as affecting the displacement of the model with respect to the fair-water when moments are being measured and as contributing another possible source of flexural vibration. The effect of this deflection is to increase the displacement of the model under a 20-pound load by 0.161 inch.

(2) The deflection of the weighing arms also has some effect, arising from two different sources, on the accuracy of the results. In the first place, since deflection throws the point of support of the weights below the horizontal plane through the main pivot when the balance is in equilibrium, the sensitivity is affected, as has been shown in another section of the report. Secondly, the instrument is balanced up initially with the cross hairs in line when the two pivots are engaged and with little or no weight on the ends of the weighing arms. It may be assumed that the weight on the ends of the arms when balancing up is just sufficient to balance the counterweights and other eccentrically placed parts, so that the center of gravity of the whole assembly is directly below the main pivot. If more weight be added, deflecting the arm, the cross hairs will no longer be in line, and if the balance axis is tilted to bring the tip of the arm back to the central position the center of gravity will be moved to one side and will exert a restoring moment when the only moments supposed to be acting are those due to the force on the model and the weights added on the weighing arms to balance that force. Obviously the error from this source is greatest when the center of gravity of the balance itself is farthest below the pivot. If the length of the weighing arm, from the pivot to the point of application of the weights, is l and its deflection is δ, the angle of rotation from the initial position of the balance in order to bring the cross-hairs into alignment after deflection is

$$\theta = \frac{\delta}{l}$$

The righting moment due to the weight of the balance being displaced with respect to the pivot is then $K \times \theta$, or $K \times \frac{\delta}{l}$, where K is the product of the weight of the balance and model by the vertical distance from the pivot to the center of gravity of the balance and model combined. It

is shown elsewhere that 47,000 gm. cm., or 40.7 pounds inches, is a fair value for K in a balance the size of the one at Langley Field. If the arms were made, as in the original N. P. L. balance, of solid steel rods $\frac{15}{16}$ inch in diameter acting as cantilevers, the deflection in a length of 23 inches under a load of 40 pounds (corresponding to 20 pounds on the model) would be 0.140 inch. With the value of K given above, this would cause the weight applied to be in error by 0.25 pound, or 0.6 per cent of the total amount. The error due to the deflection of the weighing arms, like that due to the deflection of the balance head, is directly proportional to the force acting, and the percentage error is therefore independent of the force.

On the Langley Field balance the weighing arms are steel tubes, 1 inch in diameter outside and with a wall thickness of 0.06 inch. They are trussed by tie-rods $\frac{3}{16}$ inch in diameter, and making an angle of 12°. 5 with the direction of the arm itself. The deflection of one of these arms under an end load of 40 pounds is 0.027 inch, due chiefly to the elongation of the tie-rod, if the rod and arm are perfectly straight. It is almost impossible to keep the tie-rod absolutely straight, especially where one end is screwed directly into a lug, and the actual deflection is liable to be a little greater than that computed. The deflection with tubular trussed weighing arms is, however, always much less than with solid cantilever arms of the same outside diameter, and the trussed arms also have a great advantage in respect of weight, as has been shown already. The error arising from the deflection of the weighing arms, if they are properly designed and if the sensitivity is adjusted with reasonable care before starting a test, may be disregarded.

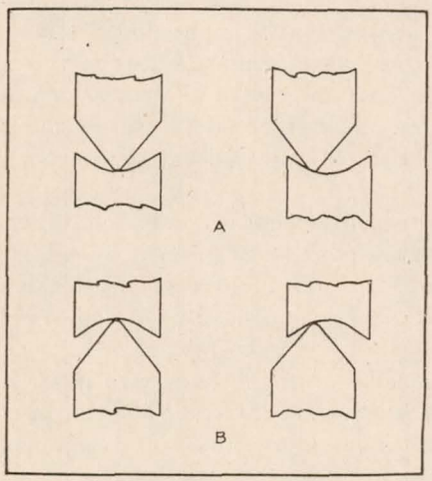


FIGURE 11.

(3) A very troublesome source of error, and one which is sometimes difficult to eliminate, is the sliding of the main pivot in its socket. If the pivot moves, the point of contact between the two surfaces will, in general, be shifted both on the pivot and in the socket. This shifting changes the moment of the weight of the balance itself about the pivot, and so changes the amount of weight which must be added to secure initial equilibrium with no force on the model. If the shifting of the pivot occurs during a run, between the times of taking the "zero reading" and that with the wind on, the change in the amount of weight required for balancing will appear as an error in the result of the measurement.

Balances may be constructed with the pivot pointing either upward or downward. In the first case the pivot is carried by the balance support; in the second case by the balance itself. Enlarged views of the two dispositions, both in the normal position and with the balance slipped slightly to one side, are shown in Fig. 11. The difference between the points of contact in the original and displaced positions is indicated in the drawings. The first type of contact considered will be that in which, as in the drawings, the pivot and socket in the neighborhood of the point of contact are each a segment of a sphere. It will be noted that when the pivot is pointing upward the point of contact moves in the balance by a distance nearly equal to the distance which the balance slips (that is, the point of contact remains very close to its original position on the support), but that, in the converse case, the movement of the point of contact in the balance is very slight. If the downward-pointing pivot rested on a flat surface the point of contact would not move at all in the balance and there would be no error due to slippage of the balance with respect to the support, but this disposition is obviously impractical, as the balance would quickly slide, impelled by the horizontal force acting on the model, into a position pressed up against the side of the socket, where it could not rock at all.

It is evident from the preceding that the pivot should be carried by the moving portion of the balance, and that it should point downward. This has another advantage in that the socket, being concave upward, can be kept filled with a thin oil to reduce the sliding friction between pivot and socket. The formula for the displacement of the point of contact in the moving portion of the balance is:

$$\xi = \frac{xR_2}{R_1 - R_2}$$

where x is the distance which the balance slides, parallel to itself, with reference to an axis fixed in space, and R_1 and R_2 are the radii of curvature of the socket and pivot, respectively. It appears from this that it would be advantageous, aside from all questions of friction, to make the pivot as sharp as possible and to employ a large radius of curvature in the socket. The first deduction is perfectly correct, but the radius of curvature of the socket is of minor importance, so far as the effect of slippage of the pivot is concerned, since it is the slope of the tangent plane at the point of contact, and not the distance moved, which limits the slip of the pivot. The ratio between the vertical and horizontal forces acting on the balance ranges between 0 and $\frac{1}{2}$ as limits, but seldom exceeds 0.35. (The value $\frac{1}{2}$ could not be reached unless the balance itself were weightless.) Taking 0 and 0.35 as the limits, it appears that the inclination to the horizontal of the surface on which the balance would rest in equilibrium, if there were no friction, lies between 0° and 19°. The pivot would rest in the bottom of the socket while the "zero readings" were being taken, and would slide up onto the inclined portion of the socket when a horizontal pressure was exerted against the model. If the total weight of the balance and model (not including the weights required to balance the force on the model) is W and the horizontal force acting is L, the angle of inclination of the common tangent to the pivot and socket for equilibrium under frictionless conditions is:

$$\phi = \tan^{-1}\frac{L}{W+2L}$$

assuming the distance from the pivot to the model to be twice the distance from the pivot to the point of attachment of the weights. The point of contact is then shifted in the balance by the amount

$$\xi = R_2 \times \sin\phi$$

and the change in moment of the moving weight about the pivot is:

$$\Delta M = R_2 \times W \times \sin\phi$$

The error in force measurement caused by this change of moment is

$$\Delta F = \frac{R_2 \times W \times \sin\phi}{h}$$

where h is the distance from the pivot to the plane of symmetry of the model. Since ϕ is always a small angle sin ϕ and tan ϕ may be considered equal. The error is then approximately

$$\Delta F = \frac{R_2}{h} \times \frac{L \times W}{W+2L}$$

In the Langley Field balance W is 28,000 gms., h is 137 cm., and the maximum value of L is about 18,000 gms. Under these conditions the possible error due to slipping of the pivot if there were no friction would be 5.75 R_2 gms., where R_2 is given in mm. The maximum percentage of error occurs when L is very small, and is, for the case just cited, $0.072R_2$ per cent. With the usual values of R_2 this is not important.

These figures have been based on the neglect of sliding friction, a factor which generally can not by any means be disregarded. If the coefficient of friction between the pivot and its socket is 0.2 the angle of inclination of the surfaces at the point of contact may be more than 5° when there is no force acting on the model. Using the figures just given, it appears that shifting of the pivot may cause a constant error of 1.2 R_2 gms.

If the socket were truly conical, there could not be any sliding of the pivot, but the sensitivity of the balance would be decreased by friction, as the slightly rounded pivot would make contact with its socket all around the circumference of a circle, and the relative motion between the two for any rocking of the balance would be sliding instead of pure rolling.

(4) A factor whose importance is frequently underestimated is the canting of the model due to inaccurate alignment of the spindle. When the spindle is screwed into an aerofoil it is very difficult to get the tapped hole exactly parallel to the leading edge, and the result is that the model usually has a distinct tilt, either in yaw or in roll, from the desired position. If the tilt is in respect of yaw the plane of symmetry of the model is no longer parallel to the wind direction. In this general case there are six forces and moments to deal with in place of the three which exist when the model is placed exactly correct. To illustrate the importance of the various factors the effect of each of the six quantities will be followed through in turn for an angle of yaw of 2°, this being a value which should not be exceeded if reasonable care is taken in fitting the spindle to the model. The forces and moments on the Clark tractor biplane model will be used in the illustrative example, these data having been obtained at the wind tunnel of the Massachusetts Institute of Technology.[1]

Denoting the forces by X, Y, Z, and the moments by L, M, and N in the usual manner, the figures with the model, of 48 cm. span placed symmetrically are, for a wind speed of 15 meters per second and various angles of attack:

Angle of attack.	0°	6°	12°
X (gms.)	58.0	74.4	123.0
Y (gms.)	0.0	0.0	0.0
Z (gms.)	207.0	615.0	899.0
L (gm. cm.)	0.0	0.0	0.0
M (gm. cm.)	0.0	0.0	0.0
N (gm. cm.)	0.0	0.0	0.0

The spindle is assumed to be located as to intersect the vector of resultant force, so that the pitching moment, as well as the other two, is zero when the model is in the position of symmetry.

At an angle of yaw of 2° the forces and movements are:

Angle of attack.	0°	6°	12°
X (gms.)	59.5	75.4	123.0
Y (gms.)	− 5.4	− 4.0	− 5.2
Z (gms.)	205.0	613.0	894.0
L (gm. cm.)	+ 71.5	+161.0	+114.0
M (gm. cm.)	+ 3.8	− 22.4	0.0
N (gm. cm.)	− 18.8	− 19.0	− 31.0

The total moment about a horizontal axis passing through the main pivot and perpendicular to the axis of the tunnel is

$$M_D = Xh \cos \psi - Yh \sin \psi + N$$

where ψ is the angle of yaw and h is, as before, the height from pivot to model. In the Massachusetts Institute of Technology balance h is 91. 4 cm.

[1] Dynamical Stability of Aeroplanes, by J. C. Hunsaker: Smithsonian Misc. Coll., vol. 62, No. 5; Washington, 1916.

The equivalent force balanced by hanging weights on the drag arm is equal to M_D divided by h, or

$$F_D = X \cos \psi - Y \sin \psi + \frac{N}{h}$$

Angle of attack.	0°	6°	12°
X	58.0	74.4	123.0
$F(\psi=+2°)$	59.5	75.3	123.0
$F(\psi=-2°)$	59.9	75.6	124.0

It appears that an angle of yaw of $-2°$ may lead to errors of from 1 per cent to 3 per cent in the measurement of the drag, and that, in order to keep the error within the desired maximum of $\frac{1}{4}$ per cent, the angle of yaw must not exceed 0°2. This ideal is perfectly possible to realize mechanically, but the spindle itself deflects at small angles so that the slope at its tip in the plane of the wing chords is slightly more than 0°2 when tests are run at 50 meters per second.

The error in lift measurement due to the model being set up at angle of yaw must be found in the same way. The total moment about an axis passing through the balance pivot and parallel to the tunnel axis is

$$M_L = Zh + M \sin \psi - L \cos \psi$$

and the equivalent force is

$$F = Z + \frac{M \sin \psi - L \cos \psi}{h}$$

The true and apparent values of Z may be tabulated as for X.

Angle of attack.	0°	6°	12°
Z	207	615	899
$F_L(\psi=+2°)$	204	611	893
$F_L(\psi=-2°)$	204	611	893

The error in lift is obviously much smaller than that in drag, and it is the accuracy desired in the latter measurement that controls the degree of precision necessary in alignment.

To complete the analysis the effect of yaw on the moments about a vertical axis must be discussed. The equation for the total moment is

$$M_V = M \cos \psi + L \sin \psi$$

Angle of attack.	0°	60°	12°
M	0.0	0.0	0.0
$M_V(\psi=\pm 2°)$	+6.3	−16.7	+4.0

These differences between the true and the apparent moments correspond to errors of 0.030, 0.027, and 0.004 cm., respectively, in the location of the vector of resultant force. These errors are negligible, the largest being less than $\frac{1}{2}$ per cent of the wing chord.

In short, then, it appears that the accurate alignment of the model in yaw is of importance primarily as regards drag and that its importance there is considerable. If the data for a single aerofoil, instead of for a complete model, are taken the importance of accurate alignment is lessened, as Y and N, which cause most of the difficulty, both arise largely from the body and tail surfaces. For bodies and other streamline forms, on the other hand, the relative importance of accurate alignment is greater than for models of complete airplanes.

The analysis of the modifications in the measurements when the model is tilted in roll instead of in yaw is much simpler, since the axis of the tunnel remains parallel to the plane of symmetry of the model, which merely rotates about it. There are, therefore, no rolling or

yawing moments or cross wind forces to be considered. The equations for moments about the three mutually perpendicular axes when the model is rolled through an angle ϕ may be written

$$M_L = Zh \cos \phi$$
$$M_D = Xh + M \sin \phi$$
$$M_V = M \cos \phi$$

The equivalent forces are

$$F_L = Z \cos \phi$$

$$F_D = X + \frac{M \sin \phi}{h}$$

The errors in lift and pitching moment are negligible for all angles of roll up to 4°. The error in drag is also very small unless M is large (i. e., unless the spindle is attached far from the line of action of the resultant force). In order that a roll of 1° may not cause an error of more than $\frac{1}{4}$ per cent in the drag when the lift/drag ratio is 16, the ratio $\frac{\epsilon}{h}$, where ϵ is the shortest distance from the axis of support of the model to the line of action of the resultant force, must not exceed 0.009. It is usually practicable to keep $\frac{\epsilon}{h}$ below this figure, at least at those angles of incidence for which the efficiency is a maximum. Since h is 137 cm. on the Langley Field balance ϵ should be kept below 1.23 cm. As has been seen in examining sensitivity, there are other cogent reasons for keeping ϵ as small as possible. The tendency of the deflection of the spindle is to set the model at a positive angle of yaw and negative angle of roll. The first of these increases the apparent drag, while the second diminishes it if, as is almost always the case, the spindle is attached to the rear of the line of action of the force on the model. The two therefore tend to counterbalance each other, and it should be possible, by the exercise of proper care in attaching the spindle to align it correctly and keep ϵ as low as possible, to insure that the resultant error due to canting of the model will not exceed $\frac{1}{4}$ per cent. The slipshod methods frequently used for mounting aerofoils on their spindles must not be tolerated.

(5) If the balance axis is not exactly vertical when pitching moments are being observed the weight of the balance itself, assuming that its center of gravity does not lie exactly on the line connecting the two pivots, and the weight placed on the scale pans to reduce the lateral pressure on the lower pivot have moments about the axis of rotation of the balance. The moments due to the attached weights are much larger than that due to the weight of the balance itself, as the length of the arm from which the weights are suspended is far greater than the distance from the axis to the center of gravity of the balance.

The balance axis will be assumed to be inclined to the vertical and to lie in such a plane that the lift arm is horizontal. This is the worst case possible, since the lift arm carries the maximum load and a weight is always most effective in producing rotation about an inclined axis when a perpendicular line from the weight to the inclined axis is perpendicular to the vertical plane in which the inclined axis lies.

If the balance axis is inclined from the vertical by a small angle θ the moment about that axis of the weight on the lift arm is $w_e \times l \times \theta$. Taking as a maximum figure for the Langley Field balance 20 kg. on the lift arm, since l is 68.5 cm. the moment due to the addition of this weight is 1,370,000 θ gm. cm. If the criterion of desired accuracy in the measurement of moments be taken to be the determination of the location of the vector of resultant force within 0.5 mm., the error in the pitching moment under the conditions just specified must not exceed 500 gm. cm. θ must therefore be less than 0.000365 radian or 0°.0209. This degree of accuracy of alignment can be secured without difficulty by making successive trials, hanging weights on the lift and drag arms (with no model in place and no wind) and taking readings of the moment about the axis through the two pivots. The scale reading under these conditions should manifestly be unaffected by the amount of weight hung on the arms.

(6) If the model is not properly lined up with the wind direction before starting a test, or, what amounts to the same thing, if the reference line used for lining up all models is not accurately located, the only effect is to produce a constant error in angle of attack, and so to shift the characteristic curves resulting from the test bodily to the right or left, according to the direction of the initial error. The maximum and minimum values of coefficients and ratios are entirely unaffected, as is the curve of lift coefficient against L/D. Although the accurate determination of angle of attack is not of much interest in routine commercial testing (if a designer can obtain a curve of horsepower required against airspeed for his machine, he is ordinarily quite satisfied without knowing the exact angle of attack corresponding to a given speed), it is of great importance in such work as the determination of correction factors for aspect ratio, etc., where a slight uncertainty as to alignment may make it quite impossible to draw any consistent conclusions from a set of tests. Provision should therefore be made for lining up wings within 0°.05 whenever it becomes necessary to do so. This degree of accuracy can be secured, with great care in sighting and with a batten carefully picked for its straightness, by the common method of binding a batten to the face of the wing and sighting it against a line painted on the floor of the tunnel, but it is more accurate and easier for the observer to use some optical method.

(7) A much more important source of error than the misalignment of the model is the misalignment of the balance with respect to the wind. In order that the lift and drag, acting perpendicular and parallel to the wind, may be measured directly the arms of the balance must themselves be set exactly perpendicular and parallel to the wind direction. If they are not, the force acting on the model will be resolved into components along some other axes than those desired and a large error may be introduced in at least one of the components.

If the components of force perpendicular and parallel to the wind direction be represented by L and D, respectively, and if the balance be supposed to rotate as a whole about a vertical axis so that the drag arm makes the angle θ with the wind direction, θ being taken as positive when the lift arm moves towards the original position of the drag arm, the lift and drag arms remaining parallel to each other, the components of the resultant force along the two arms will be

$$L \cos \Theta + D \sin \Theta \text{ for the lift arm, and}$$
$$D \cos \Theta - L \sin \Theta \text{ for the drag arm.}$$

Multiplying and dividing by appropriate factors, these become

$$F_L = L \cos \Theta \left(1 + \frac{D}{L} \tan \Theta\right)$$

$$F_D = D \cos \Theta \left(1 - \frac{L}{D} \tan \Theta\right)$$

Even with the utmost carelessness in lining up the balance, Θ should never exceed 1°. Since the ratio of lift to drag is at least three for all objects on which accurate measurements of the lift are desired, the error in L due to misalignment should not, under any conditions, be greater than 0.6 per cent. This is an error by no means negligible, but still not very important, inasmuch as it reaches its maximum only when the L/D is low (e. g., in the neighborhood of the burble point). For wings and models of complete airplanes at angles in the region of high efficiency the error in lift measurements arising from a misalignment of the arms by 1° is well within ¼ per cent.

The error in drag is much more serious, particularly as it is largest at the point of maximum efficiency, just where accurate measurements are most desired. For a good wing, having a value of L/D of 18, the error in drag measurement when θ is 1° is more than 30 per cent. If the drag is to be measured accurately within one-fourth per cent, the balance must be lined up with the drag arm parallel to the wind to within 0.008°. A similar relative accuracy of measurement of the drag with models of complete airplanes, having a maximum L/D of 8, requires an alignment correct within 0.018°. Such accuracy as this is hardly to be expected, and errors in alignment of the balance arms are the largest single cause of error in the determination of the L/D at small angles; but a surprisingly close alignment (well within 0.05°) can be secured and maintained by careful setting up of the instrument and constant checking

The method originally used in this country for aligning the balance arms with respect to the wing in balances of the N. P. L. type required the use of a flat plate. This was tested at several positive and negative angles. If the plate, the balance arms, and the wind direction were all properly disposed with respect to each other, the lifts for equal positive and negative angles should be equal in magnitude but opposite in sign, and the drags should be equal. If the first of these conditions was fulfilled but the second was not, it indicated that the zero angle of attack had been properly located, but that misalignment of the balance arms existed. The flat-plate method was unsatisfactory chiefly because of the low efficiency of such a surface. It has just been shown that the error in drag measurements caused by misalignment of the arms is proportional to the L/D ratio. When the L/D ratio is small, therefore, as it always is in a flat plate, it is exceedingly difficult to detect small errors in alignment, errors which may nevertheless have an important effect on the measurement of drag in a high-efficiency wing. Furthermore, it is difficult to secure a plate which is and will remain truly flat. Inaccuracies of surface too small to be detected by any ordinary means of measurement may cause a distinct difference between the lift-drag ratios at equal positive and negative angles. This difficulty was overcome in part by repeating the work with the plate turned through 180° about a vertical axis.

The method now adopted and first introduced by the N. P. L. several years ago substitutes a model aerofoil for the flat plate. The aerofoil is drilled and tapped for a spindle at each end, so that it may be supported in an inverted as well as in the normal position. Tests are then run in both positions and the L/D curves compared. Since the lift in the inverted position must be balanced by the removal of weight from the lift arm, it is usually necessary, in order that angles up to 6° or 8° may be taken in this condition, that more weight be added to the lift counterweight, thereby increasing the zero reading. This method permits of much more accurate alignment than does the flat-plate method. Its only important drawback is that the model has to be taken down and set up again between tests; but, as already pointed out, the chords for zero angle of attack in the two positions can be set parallel within 0°.05 by sighting along a batten, if care is exercised. The disadvantage is therefore not a serious one.

The use of an aerofoil in normal and inverted positions for checking up the alignment has another advantage in that it points the way to eliminating the effect of spin in the air-stream. The air drawn into the propeller has a tendency to follow a helical path of very large pitch-radius ratio, so that the direction of the wind near the top of the tunnel is slightly different from that near the bottom. If the direction of motion changes uniformly from top to bottom of the tunnel, the force acting on a wing would be almost identical with that which would act if there were no spin of the wind and if the direction of its motion were everywhere the same as that which actually prevails at the center of the span of the aerofoil. The readings of the balance in the two cases, however, would not be the same, since the moment arm about the pivot is different for different elements of the model. For example, consider two elements of equal area and at equal distances from the center of the span. The forces on the two elements will then be $F+\Delta F$ and $F-\Delta F$, where F is the force acting on an element of the same size located at mid section, and the moment arms about the pivot will be $h+\Delta h$ and $h-\Delta h$. The moments for the two will then be

$$(F+\Delta F)\ (h+\Delta h) \text{ and } (F-\Delta F)\ (h-\Delta h).$$

The mean of the forces on the two elements is, as already noted, equal to F, the force which would exist everywhere if there were no spin. The mean of the moments is

$$\frac{(F+\Delta F)\ (h+\Delta h)+(F-\Delta F)\ (h-\Delta h)}{2}=(F\times h)+(\Delta F\times\Delta h)$$

and is therefore different from the moment of an equal area at the middle of the wing. If, however, the wing be aligned so that the lifts at corresponding angles are equal in the normal and inverted positions, the force read on the weighing arm is the true one, and the effect of spin is eliminated. When the wing is set at zero angle of attack after being lined up in this way, the

chord is not exactly parallel to the wind direction at mid span, but the readings of the weighing arms are identical with those which would be obtained if there were no spin in the wind and the chord were set parallel to the wind direction. The alignment found in this way varies slightly with the slope of the curves of lift and drag coefficients; and it also requires, for accuracy, that the form of the aerofoil section be exactly symmetrical from tip to tip. It is best, therefore, to carry through the work of alignment with two or three different models in succession and at several angles for each model. It is difficult to determine the maximum possible error due to misalignment in any specific case, but it is probably not over 1 per cent under the worst conditions when the balance is lined up carefully by this method.

(8) Closely allied to misalignment of the model with respect to the wind, in that the primary effect of both is to cause an error in the determination of the angle of incidence, is the torsion of the spindle. The total twist of the spindle is negligible when a straight spindle is used attached directly to the end of an aerofoil, since the torsional moment is then very small. For example, with a force of 20,000 gms. applied 1 cm. from the center of the spindle 23 cm. long and tapering in diameter from 25.4 mm. to 14.3 mm., like that used at Langley Field, the twist would be less than 0°.05. There should never be any difficulty in keeping the spindle within 1 cm. of the center of pressure of the chord at the angle of maximum lift. In complete models, where it is not always posssible to attach the spindle at the desired point, other parts of the model interfering, and where the point of application of the resultant force moves over a wider range than on a single aerofoil, this limit may sometimes be exceeded five or six times, so that the maximum twist may be 0°.3 or or a little more. This offers an additional reason for so locating the spindle as to keep the pitching moment as small as possible. Even 0°.3, however, is ordinarily of slight importance except where accurate checks on two or more successive tests with some slight variation in the conditions are desired. As has already been pointed out, errors in angle of incidence up to about a quarter of a degree need cause no trouble in ordinary tests of complete models.

(9) The errors so far discussed have all arisen either from such inescapable phenomena as the deflection of the spindle or from improper mounting and alignment of the instrument or model Those which remain to be discussed are due to errors in the construction of the balance itself, and may all be eliminated or reduced to insignificance by sufficiently accurate workmanship. The analysis of the sources of these errors and of the magnitudes which they may assume is of value primarily in that it indicates the accuracy necessary in the construction and assembly of the different parts.

The first, and perhaps the most obvious, of the points at which errors arise from failure to follow the designs with absolute exactitude is the length of the weighing arms. Obviously, if the weighing arms, or either one of them, are longer than they are intended to be, a weight suspended at the end of the long arm will balance a force at the center of the tunnel of more than half its own magnitude. The error in the reading will be directly proportional to the departure from the designed length. The permissible error in measurement has so far been taken as one-fourth per cent, but this will be reduced, in the case of the constant instrumental errors, to 0.1 per cent from each source. It is then permissible for the weighing arms to vary in length 0.1 per cent in either direction, or, in the Langley Field balance, 0.68 mm. A skilled man should not have the slightest difficulty in keeping the error down to one-fourth of this amount, and the accuracy sometimes sought for in this particular is really quite needless.

The same consideration of course applies with regard to the distance from the pivot to the center of the model, the permissible variation here being twice as great as that in the lengths of the weighing arms. If there is an error in this distance, or if there is a common error in the lengths of the two weighing arms, the leverage ratio can be restored to its proper value by modifying the distance which the spindle of the model is allowed to project from the chuck which attaches it to the balance.

(10) Another difficulty in connection with the weighing arms is their attachment exactly at right angles to each other. If they are not so attached errors will be caused in the measurement of the lift or drag, or both. The analytical work involved in the determination of these errors need not be followed through in detail in this report. If the arms are not at right angles the

alignment of the arms in order that the lifts and drags may both be the same at equal angles of an aerofoil in the normal and inverted positions will be different for every different aerofoil used and for every angle at which the tests for alignment are carried out. If, however, the alignment be supposed to have been carried out to satisfy the above condition as accurately as possible for a given model and angle of incidence there will still be an error in both lift and drag. The ratio of relative error between the two components is proportional to the ratio of the slope of the coefficient curves to the ordinates of those curves at the particular angle for which alignment was carried out. At all angles between that of minimum drag and that of maximum lift the error in both components is in the same direction, so that the error in L/D is less than that in either component alone. The balance readings are farthest astray from the true values in measuring the drag near the burble point, where a variation of 0°.1 in the angle between the arms may lead to an error of nearly 2 per cent in the drag. This error falls off rapidly at angles smaller than the burble point, and the mistake made in the determination of the forces at angles between 0° and 8°, the range which is of most interest, would never be more than 0.03 per cent for a departure of 0°.1 from a right angle between the arms. An accuracy of 0°.3 in this angle is quite sufficient, if the balance is lined up in the manner here described, and if, in lining up, tests are made at several angles lying between 2° and 8°, the mean result being taken.

(11) If the strut and spring clamp which prevent the balance from rotating about a vertical axis are not horizontal the force which they exert against the arm will have a vertical component and will change the amount of weight which must be placed on the lift arm to secure equilibrium. If there is no pitching moment on the model the upward or downward component of the thrust of the strut against the arm will be exactly balanced by an equal and opposite component of the pull of the clamp. If there is a pitching moment, however, one of these two forces will be greater than the other and there will be an unbalanced vertical component. Assuming the moment arm of the resultant force with respect to the balance axis to be 4 cm., the moment is approximately $4L$, where L is the lift. This moment has to be balanced by the difference between the forces in the strut and spring clamp. If the vertical component of this difference is not to cause an error of more than 0.1 per cent in the measurement of L it must be less than $\frac{L \times h}{1,000}$, and the slope of the strut must not be greater than

$$\frac{L \times h}{1,000 \times 4L} = \frac{h}{4,000}$$

For the Langley Field balance this formula gives a limiting slope of 2°, a limit which would hardly be approached if any special precautions were taken.

(12) If the strut and clamp are horizontal, but are above or below the main pivot, the difference in the forces which they exert will have a moment tending to modify the reading of the drag arm. Since the distance between the pivot and the point at which the strut bears against the lift counterweight arm is; in the Langley Field balance, 30.5 cm., the difference in the two opposing forces is, for a moment of $4L$, $-0.13L$ gms. If ζ be the vertical distance from the horizontal plane through the main pivot to the point of contact of the strut the moment of the unbalanced force is $0.13L \times \zeta$, and its existence changes the reading of drag by

$$\frac{0.13L\zeta}{h}$$

This must be less than 0.1 per cent of D. Then

$$\frac{0.13L\zeta}{h} < \frac{D}{1,000}$$

$$\zeta < \frac{h}{130} \times \frac{D}{L}$$

In the case of the Langley Field balance, for an $\frac{L}{D}$ of 16, this leads to the conclusion that ζ must not exceed 0.07 cm.

(13) The strut and spring clamp bear in conical sockets opposed to each other. Both sockets are cut in a single piece of tool steel, and a great deal of care has been used in some cases to bring their apices as close together as possible without actually having them break through and meet. In some cases the bottoms of these sockets have been brought within 0.08 mm. of each other. Theoretically the two should be at a common point, and any separation between them introduces an error. The effect of a separation between the pivots of the strut and spring clamp will be analyzed first with regard to its effect on the measurements of lift and drag.

So long as the two sockets which carry the ends on the strut are on the same level the strut and spring clamp lie in the same plane, whatever the separation may be. If they are not on the same level, however, and it has just been shown that the line connecting them may slope 2° initially without serious effect, or if the balance rocks about the drag arm as an axis so that the end of the lift counterweight arm rises and falls, the two pieces no longer lie in the same plane, and the lines of action of their thrusts are no longer directly opposed. It will be supposed that there is no pitching moment acting, this being the condition during the taking of the zero readings, that the socket set in the end of the lift counterweight arm is initially as far above that set in the moment weighing arm as is safe (see (11)), and that the lift weighing arm is down as far as the stops in its cage permit it to go, so that the counterweight arm is up and the vertical distance between the ends of the strut is as large as it can ever be. The condition then existing is shown, much exaggerated and with the strut and spring clamp represented only by their center lines, in Figure 12. If F be the compression in the strut and also the force exerted by the spring clamp against its socket, the two being equal when there is no pitching moment, the moment about the lift arm due to the separation of the apices of the sockets is equal to the product of F by the distance between the lines of action of the two members at the point half-way between the apices of the sockets in the lift counterweight arm. Since $\Delta\alpha$ is negligible in comparison with α, this distance is $\epsilon \times \sin\alpha$, and the moment is

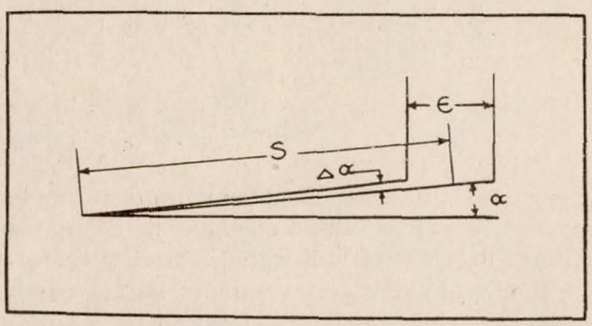


FIGURE 12.

$$F \times \epsilon \times \sin\alpha$$

The moment required to change the weight on the drag arm by 0.1 per cent is

$$\frac{D \times h}{1{,}000}$$

where h, as before, is the distance from the main pivot to the center of the model. Equating these two moments,

$$\frac{D \times h}{1{,}000} = F \times \epsilon \times \sin\alpha$$

$$\epsilon = \frac{D \times h}{1{,}000 \times F \times \sin\alpha}$$

In the particular case of the Langley Field balance h is 137 cm., the maximum likely to be attained by α is 3°, and the maximum of F is 8 kg., a maximum which would not be needed except at high wind speeds. Normally, the spring clamp would be adjusted for a smaller force unless the lift were at least 15 kg. D may then be assumed to be 1 kg. Substituting these figures in the formula above,

$$\epsilon = \frac{1{,}000 \times 137}{1{,}000 \times 8{,}000 \times 0.0523} = 0.328 \text{ cm.}$$

The separation between the apices of the pivot sockets also has an effect on the measurement of lift. The horizontal components of the forces in the strut and spring clamp are, as already noted, exactly equal and directly opposed, but the vertical components differ because of the slight difference in slope. This difference in slope is $\Delta\alpha$. Since α is small, the difference in vertical components is very nearly equal to $F\times\Delta\alpha$, and this is approximately

$$F\times\frac{\epsilon\times\sin\alpha}{s}$$

where s is the length of the strut.

If the socket at the end of the lift counterweight arm is at a distance (a) from the main pivot, the force corresponding to the moment about the main pivot resulting from this unbalanced vertical force is

$$F\times\frac{\epsilon\times\sin\alpha}{s}\times\frac{a}{h}$$

Equating this to $\frac{L}{1{,}000}$, the allowable error, it is seen that the limiting value for ϵ is:

$$\epsilon=\frac{L\times s\times h}{1{,}000\times a\times\sin\alpha\times F}$$

In the Langley Field balance a is 30.5 cm., s is 5.9 cm., and F should never exceed $\frac{1}{2}$ L. Then

$$\epsilon=\frac{L\times 5.9\times 137}{1{,}000\times 30.5\times 0.0523\times\frac{1}{2}L}=1.01\text{ cm.}$$

It is evident that the first case, relating to the error in drag, is the limiting one, and it is also apparent that it is useless spending much time in attempting to bring the apices of the sockets within a fraction of millimeter of each other. If they approach within 3 mm. in a balance of the type and size of that built by the advisory committee the errors resulting from the separation will be negligible, at least so far as lift and drag are concerned.

It has been assumed thus far that there is a separation between the apices of the sockets at one end only, and that the distance between the opposite ends of the strut and spring clamp is negligible. If this is not the case, there being an equal separation at both ends, the error in drag is not affected, while that in lift is doubled. The drag, however, still remains the limiting factor and the permissible separation therefore is not altered.

In measuring pitching moments the separation of the pivots causes an error similar to that arising in the drag from the same reason. If the sockets at the ends of the strut are on exactly the same level there is no error. In order that the error with the strut inclined 2° may not be over 250 gm. cm. when the lift is 10 kg. the separation of the pivots must be less than 0.365 cm. The drag, therefore, still furnishes the limiting case.

(14) The upper balance head is restrained laterally by a flange which projects down from the upper head into the lower one, and also by the tubular portion of the clamping ring. If the centers of these guiding rings are not exactly coincident with the line connecting the main and lower pivots, or if the surface of contact between the upper and lower parts of the balance is not perpendicular to the line joining the pivots, the center about which the model rotates when taking moments will not be correctly determined by the usual method. Since an error in the location of the center of rotation corresponds to an error of like absolute magnitude in the position of the vector or center of pressure in the model, the standards of accuracy which have been adopted require that this error shall not exceed 0.2 mm. In the Langley Field balance, the securing of this degree of accuracy exacts that the line connecting the pivots shall be perpendicular to the surface of separation between the heads within 0°.009. A movement of the lower pivot through 0.12 mm., due to bending of the lower tube, will throw the line connecting the pivots out by this angle, and it is therefore necessary that the lower tube be straightened and adjusted with great care, and that the perpendicularity of the line and surface defined above be checked frequently.

(15) Analogous to the error just discussed is that resulting from lateral play between the upper and lower heads of the balance, which changes the axis of rotation of the upper head relative to the line connecting the pivots. This lateral play, however, has another bad effect in that it moves the center of gravity of the upper head and so changes the amount of weight required on the weighing arms for the zero reading. If the upper head moves after the taking of the zero and before that with the wind on is secured there will be a resulting error

$$\epsilon \times \frac{W'}{h}$$

where ϵ is the lateral movement and W' is the weight of the upper head with all the parts directly attached to it. With a model of average weight, W' for the advisory committee's balance is about 6 kg. In order that the error in drag due to the slippage of the upper head may not be more than 0.5 gm. ϵ must not exceed 0.11 mm., and the clearance between the annular flange and the cylindrical portion of the lower head into which it fits should be kept below this figure.

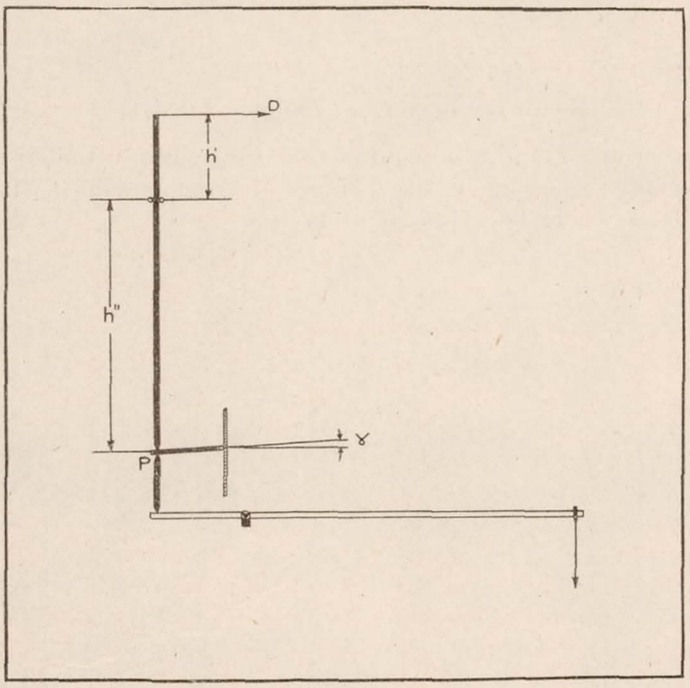


FIGURE 13.

ERRORS IN THE VERTICAL-FORCE MEASUREMENTS.

There are certain errors in this part of the balance which are obvious and are strictly analogous to those already considered for lift and drag measurements. An error in the length of the V. F. weighing arm, for example, has just the same effect as has a corresponding slip on the weighing arms for lift and drag. The knife-edge on the V. F. arm must be located with some care, as one arm of the beam (the one extending from the knife-edge through the balance wall to the center) is very short and only a small absolute error (about 0.1 mm.) is permissible. It is, however, easy to calibrate the V. F. arm with dead weight, and to adjust the knife-edges in accordance with the calibration.

The most serious fault to which the V. F. measurements are liable arises from the inclination to the horizontal of the link which is fastened to the wall of the balance and which carries the socket for the lower end of the long vertical rod. If the strut which runs vertically from that link to the inner end of the V. F. weighing arm is too long or too short the link will not be horizontal, and any force in it will have a vertical component causing an error in the measurement of the vertical force. The method of determining whether or not this error exists has been described elsewhere,[1] and it will suffice here to determine the magnitude of the error resulting from a given departure from the correct length of strut or, conversely, the accuracy with which the strut must be made to keep the error within a given tolerance.

[1] Report of British Advisory Committee for Aeronautics, 1912-13, p. 65: London.

The arrangement of the vertical force mechanism is shown diagramatically in Fig. 13. Taking moments about the rollers at G, at which point the force against the rod must be exactly horizontal if the friction in the rollers be neglected, the force at P is seen to be

$$D \times \frac{h'}{h''}$$

The vertical component of this force is

$$D \times \frac{h'}{h''} \times \gamma$$

Since this is subtracted from the vertical force acting on the model it increases the apparent magnitude of the force. In order that the error in lift from this cause may not exceed 0.1 per cent the slope of the link must be less than

$$\gamma = \frac{L}{D} \times \frac{h''}{h'} \times \frac{1}{1{,}000}$$

In the case of the balance at Langley Field, if the minimum $\frac{L}{D}$ be taken as 5, γ must be less than 0°.75, and this requires that the length of the strut be correct within 1 mm. Here, as in many others among the sources of error examined, the tolerance in dimensions is much larger than would be expected at first.

REPORT No. 72.

PART IV.

BRIEF NOTES ON BALANCES OF OTHER TYPES.

In discussing other types of balances, no attempt will be made to carry through any such exhaustive analysis of sources of error as has been developed for the N. P. L. instrument. The endeavor will be rather to show the reasons which led to the rejection of these other types in favor of the one finally adopted for construction and use at Langley Field.

(1) EIFFEL.

The principle of operation of the Eiffel balance is fully explained in his two books.[1] The essential parts of the instrument are shown diagrammatically in Fig. 14. Three readings are taken at each angle of incidence, determining the moments about axes A, B, and C. From these three values can be computed the magnitude and line of action of the resultant force on the model. In the actual instrument used at the Eiffel laboratories only two axes are used, C being omitted, and the moment about A is taken both with the model in the normal position and with the model inverted. The moments about A in the normal and inverted positions, respectively, will be denoted by M_A and M_A', the moment about B by M_B.

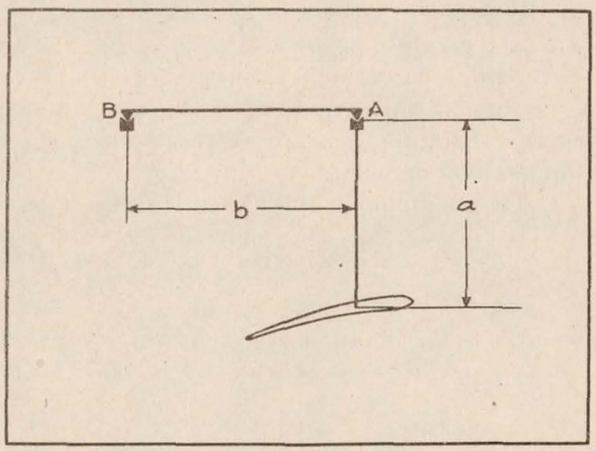


FIGURE 14.

If the force acting on the model be resolved into its components L and D, acting at the point shown in the diagram, and the pitching moment M, the equations for moments about the three axes can be written, assuming the model to be set up with the origin of its axes directly under A,

$$M_A = (a \times D) - M$$
$$M_A' = (a \times D) + M$$
$$M_B = (a + C) \times D - (b \times L) - M$$

Solving these equations, the formulae for L, D, and M can be secured.

$$L = \frac{-M_B + (M_A' \times \frac{c}{2a}) + (M_A \times \frac{2a+c}{2a}}{b}$$

$$D = \frac{M_A + M_A'}{2a}$$

$$M = \frac{M_A' - M_A}{2}$$

Ordinarily M_B is negative, M_A and M_A' positive. L and D are therefore obtained by summations, M by a subtraction.

[1] Recherches sur la Resistance de l'Air et l'Aviation, G. Eiffel, Paris, 1911. Nouvelles Recherches sur la Resistance de l'Air et l'Aviation, G. Eiffel, Paris, 1914.

Since the three moments are taken at different times the errors which appear in any two of the three due to variations in wind speed may be in the same or in opposite directions, and the worst of these conditions must be assumed in computing the maximum error which can enter into the computed quantities. The maximum error to be expected in any single measurement is approximately proportional to the magnitude of the measurement unless this is very small, as most of the error is caused by fluctuations in wind speed or by inaccuracies in its measurement. L and D are the results of summations, and the maximum percentage error in these forces therefore can not exceed the maximum percentage error in the factors from which they are determined. There should be no difficulty in keeping this below $\frac{1}{2}$ per cent. The only restriction that must be observed in order not to impair the accuracy of measurement of L and D is that the distance b must be large enough so that M_B will never become positive, or even approach very near to zero, under any ordinary conditions. This requirement will be satisfied if b is one-half as large as a. In Eiffel's balance b appears to be unnecessarily large, being approximately equal to a.

The errors arising in the computation of pitching moment are likely to be more serious, since that quantity is the difference of two moments. The error which is of interest here is absolute and not relative, a mistake of 10 gm. cm. in a given model being quite as serious if the total moment is 10,000 gm. cm. as it is if the spindle is so placed as to reduce the moment to 100 gm. cm., since it is the line of action of the resultant force which has to be determined with the greatest possible accuracy, and the shifting of this line by an error in determination of the pitching moment is proportional to the absolute magnitude of that error and inversely proportional to the resultant force on the model, but is entirely independent of the point taken as an origin, the location of this point being the chief factor determining the magnitude of the pitching moment.

The maximum absolute error in the computed pitching moment is

$$\Delta M = \frac{(\delta \times M_A) + (\delta \times M_A')}{2} = \delta \times a \times D$$

where δ is the maximum proportional error in a single measurement.

The error in the location of the resultant force is then nearly

$$\Delta X = \frac{\Delta M}{L} = \frac{\delta \times a}{\frac{L}{D}}$$

In the balance used at Eiffel's laboratory, a is approximately 10 times the chord of the models usually tested. Then, if l is the chord,

$$\Delta X = \frac{10\delta \times l}{\frac{L}{D}}$$

Taking L/D as 16 for wings, and δ as 1/200, a possible error of a little more than 3 per cent of the chord in locating the center of pressure is indicated. For complete models, having a maximum L/D of 8, the error in locating the vector of resultant force may be as much as 6 per cent of the chord. For angles of attack other than those of maximum L/D the possible error is still greater. This large error is inherent in the Eiffel type of balance, and no modification of the dimensions can remove it. It can be somewhat reduced by reducing a, but steps in this direction are limited by the necessity of keeping the weighing beam and main supporting frame of the balance out of the moving air; a must, therefore, be at least half the diameter of the wind-stream.

This discussion has so far been based on the assumption that the moments about the various axes are not affected by any errors in the instrument itself. Actually, however, the spindle is quite as subject to deflection as in an N. P. L. balance. Since the bending moment

in the spindle at any particular point is not the same when the model is in the normal position as when it is held inverted at the same angle, the deflection will not be the same in the two cases. The moment about A in each position therefore includes a term proportional to the lift, and this term is different in the two positions. The failure to take account of the deflection of the model leads to errors in the computation of both forces and the pitching moment. The unequal deflections of the weighing arm when taking the two moments lead to an error of the same nature. The error in the drag from this cause may be as much as 3 per cent with a spindle of normal size, and the percentage error increases as the wind speed increases. If the spindle is enlarged to cut down the deflection it becomes a matter of great difficulty to allow for the increased spindle interference.

Furthermore, the drag of the model is not the same in the normal and inverted positions, because the effective drag of the spindle, due largely to interference, is quite different when it is attached on the upper surface of the wing from that when the spindle is mounted on the lower surface. This causes a further error in computing the pitching moment.

No detailed discussion of the errors arising in the Eiffel type of balance will be undertaken. Its chief disadvantages, in addition to the inherent inaccuracies already noted, are the time required for taking all the readings and working up the results therefrom, its great weight (the moving parts of the balance at Eiffel's laboratory weigh 50 kg., although it is never required to measure forces in excess of 10 kg.), and its lack of sensitivity, discussed in the next paragraph. Its only important advantages reside in the elimination of all pivots in favor of knife-edges and in the avoidance of serious errors due to failure to line the balance up to the wind accurately. If the axes about which moments are taken are not exactly perpendicular to the wind direction it is a matter of small import.

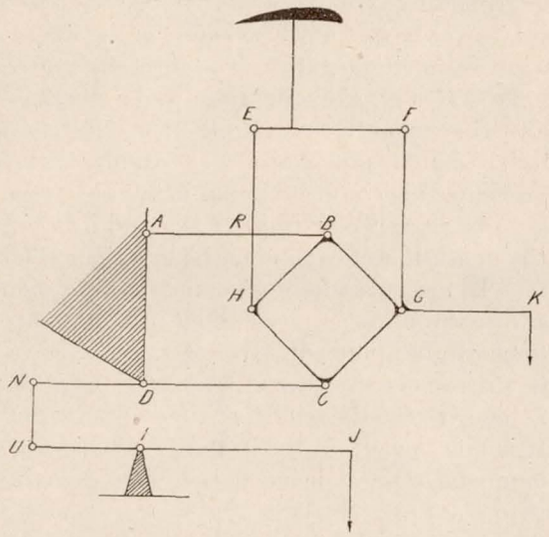


FIGURE 15.

The sensitivity of the Eiffel balance is rather low, as the main portion of the instrument is supported on a pair of knife-edges, and these knife-edges are at the extreme top of the floating member. The center of gravity of this main beam is, judging from the drawings, about 35 cm. below the knife-edges, and there is consequently a large restoring moment due to the weight of the instrument when the beam is moved from the central position. The lack of sensitivity due to this cause could be balanced by placing the center of gravity of the weighing-beam well above the knife-edges on which it is supported, so that this member alone would be unstable, but this does not appear to have been done in the instrument used by Eiffel. No dash pot is incorporated, and it is therefore necessary to secure a good degree of stability of the beam in order that it may not make continuous violent oscillations between the stops.

(2) THE ST. CYR. BALANCE.

The balance used in the tunnel of the Institut Aerotechnique de St. Cyr is quite different from any of the older and better-known types, and it embodies many original and interesting features. The general arrangement is shown in Fig. 15. *ABCD* and *EFGH* are articulated parallelograms. *BGCH* is a rigid square frame.

The lift on the model causes the parallelograms *EFGH* and *BGCH* to rise, and *CDN* pivots about *D*. The upward movement of *C* is transmitted through the links *CDN* and *NU*, and raises the outer end of the weighing beam *UIJ*. Weight is added at *J* until this tendency to rise is balanced.

In measuring the drag the wing moves horizontally, GH acts as the fixed link, FGK pivots about G, and the drag is measured by weights at K.

Since AD is fixed in the frame of the balance, AD and BC always remain vertical, EF and GH horizontal. The model, therefore, moves parallel to itself, and the angle of attack never changes, nor do its slight movements cause it to assume any angle of roll or yaw. In this respect the St. Cyr balance has the advantage over the N. P. L. instrument.

The two measurements can not be entirely independent, as the weight attached at K exerts a direct downward force as well as a moment about G, and the lift is therefore greater than that read at J. Since the lift is the sum of two figures, the error is no greater than it would be if the lift were obtained by a single measurement.

Adjustable weights are carried on prolongations of EH and FG below the lower pivots, and these serve to adjust the position of the center of gravity and control the sensitivity with models of different weights.

All pivots are eliminated in this balance, knife-edges or ball-bearings being used at all joints. This, and the uniformly parallel motion of the model, are the greatest advantages of the St. Cyr type of balances. There is an objectionably large number of joints, 11 in all, as against the single pivot and the two universal joints provided by the strut and spring clamp in the N. P. L. instrument. The St. Cyr balance escapes some of the errors to which the simpler type is subject. As in the Eiffel balance, the alignment of the plane of the linkage with respect to the wind is not important. The force balanced by the weights at K is that perpendicular to the links EH and FG, and these links must therefore be very closely perpendicular to the wind direction when the weighing arm is in its neutral position. The departure from perpendicularity should not exceed 0°.05 under any conditions, and, since deflection either of FG or GK prevents this condition from being observed, those arms must be extremely stiff. If alignment is to be preserved within 0°.05, and if the deflection length ratio for FG and GK is the same, the deflection of each must be less than 1/2300 of its length.

To measure pitching moments, a pin is inserted at R locking the two parallelograms together and maintaining each of them in rectangular form. The model and the parallelogram $EFGH$ then rotate about A. In order that this motion may be free it is necessary that the link CD be disconnected either at C or at D as, if this were not done, C would also rotate about A and, D being fixed, the length of the link CD would have to change in order to permit of any motion. It is not clear from the drawings what provision, if any, is made for such disarticulation. The moment about A being balanced by hanging weight on at K, the perpendicular distance from A to the force vector can be computed and, its slope being known from the force measurements, the vector is fully defined as to length and line of action.

It is thus necessary to make two runs with this balance, just as with the N. P. L. instrument, for a complete determination of the forces and moment acting on a symmetrical object.

A number of other devices are incorporated in the balance for increasing the ease of reading and decreasing the work of computation involved. For example, there are a pair of small hydraulic dynamometers which permit the direct measurement of forces without the use of any weights at all. Special means are also provided for eliminating the zero reading on both weighing arms and for taking care of negative lifts, as well as for balancing the lift, due to the lowered static pressure inside the tunnel, on the flanged ring which dips into the oil seal.

(3) CURTISS.

The balance designed by Dr. A. F. Zahm for the 4-foot tunnel of the Curtiss Engineering Corporation is similar to the N. P. L. type in general, but differs from it in that the single pivot is replaced by two sets of knife-edges at right angles to each other. The lift and drag are then measured on separate runs. The knife-edges are carried at the extreme ends of the weighing arms, so that there is no possibility of one knife-edge being lifted from its socket by the transverse force on the model unless the lift is nearly equal to the total weight of the balance.

The use of two independent sets of knife-edges makes it possible, if desired, to secure different degrees of sensitivity in lift and drag. A much higher degree of absolute sensitivity is

usually necessary in drag than in lift, and some stability in respect of the lift measurements is useful, especially at large angles where the lift arm tends to oscillate violently.

It was shown in Part II that the synchronism of the movements of the model in two planes affects the sensitivity in lift, the lift being modified by the angle of yaw which the model assumes when the drag beam moves from its neutral position. This effect obviously does not appear in the Curtiss balance, where the measurements of lift and drag are taken at different times.

In respect of most of the errors discussed in Part III, and of the accuracy necessary in the sliding of various parts, the Curtiss balance stands on exactly the same footing as does the N. P. L. type. The balance carried on two widely separated knife-edges obviously needs no strut and spring clamp to prevent rotation about a vertical axis, and the elimination of these members, together with the natural superiority of a knife-edge over a pivot makes the friction in the Curtiss balance materially smaller than that in the single-pivot type. The only important counterbalancing disadvantage is the time required to make two separate runs.

Pitching moments are measured by an entirely self-contained device, making no contact with the frame. The model is carried on a rod which passes down through the hollow upper portion of the balance. The lower end of the rod is pointed and rests in a conical socket. This rod has attached to it a horizontal bar which projects through a hole in the wall of the balance, and which bears against the end of the vertical arm of a bell crank, on the horizontal arm of which weight is hung to balance the pitching moments. The moment guide arm is carried by the upper part of the balance proper, which therefore never makes any contact with the balance frame except through the knife-edges. This method of measuring moments is essentially similar in principle to that used at Langley Field, has the same merits, and is subject to the same criticisms.

(4) WRIGHT.

In the balance designed by Mr. Orville Wright, and used in his wind tunnel at Dayton, the L/D ratio can be found directly by measuring the slope of the vector. The model is carried by one side of an articulated parallelogram, the opposite side of which is fixed relative to the tunnel. The model therefore moves parallel to itself, and takes up a position such that the two free sides of the parallelogram are parallel to the vector (if the plane of the linkage is vertical, the vertical links must, of course, be prolonged and counterweighted, the counterweights being adjusted so that, with the model in place and no wind on, the linkage will remain in any position in which it is set).

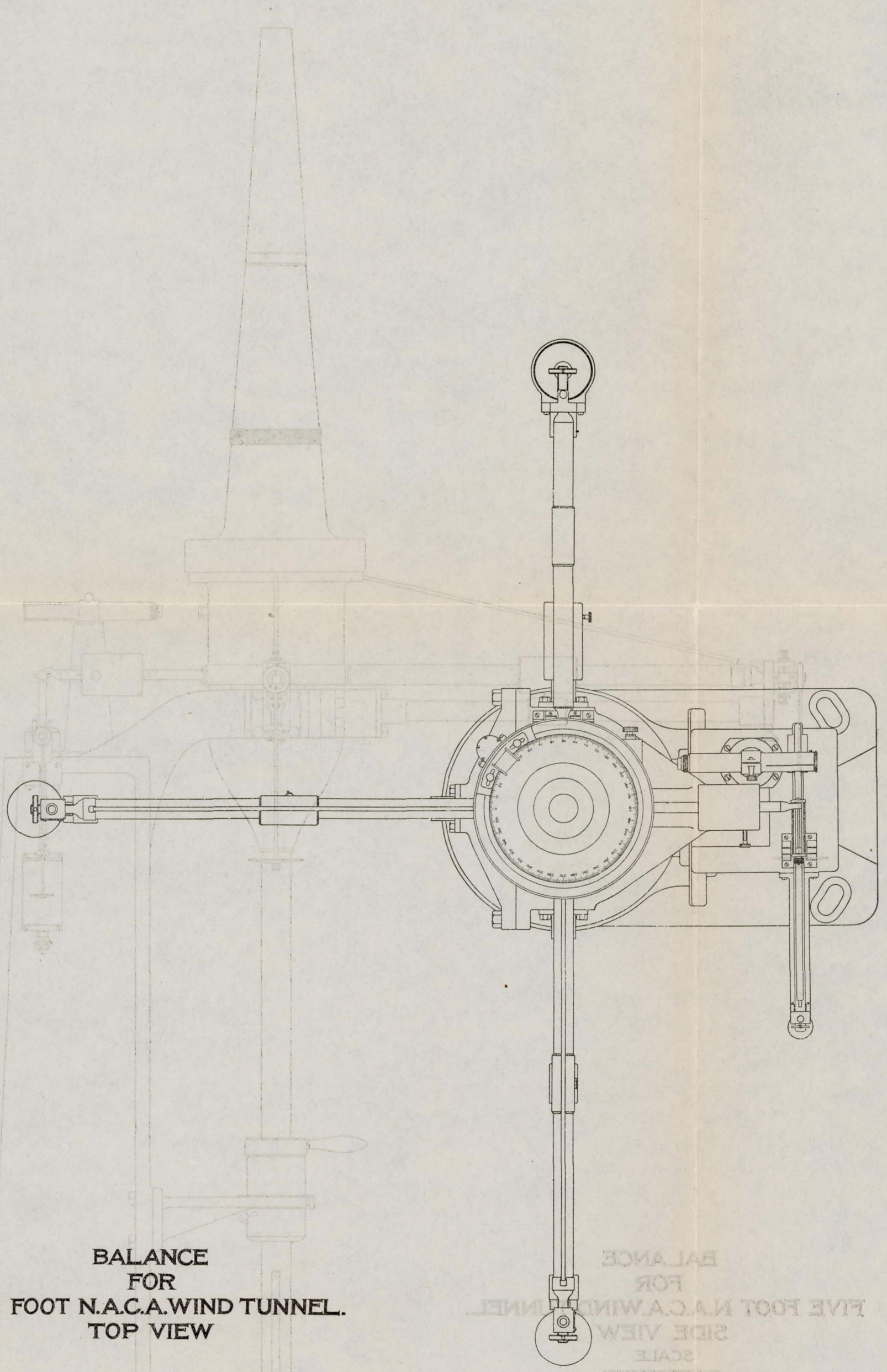
The major disadvantage of this system is the minuteness of the angles which must be measured. If an L/D of 16 is to be determined with an error not in excess of 1 per cent, the slope of the vector must be read off correct within 0°.036. This corresponds to a distance of 0.16 mm. at the tip of a pointer 25 cm. long. The difficulty of reading angles as closely as this must always be considerable, even if the pointer remains perfectly steady. With care, however, the flexible linkage method is capable of giving very accurate results.

When the lift and drag are to be measured separately these forces are balanced against the drag on a wire screen. The force is read directly from the position of a pointer on a scale, and no such adjustments are necessary as had to be made in the Lanchester and Dines balances (see Part II).

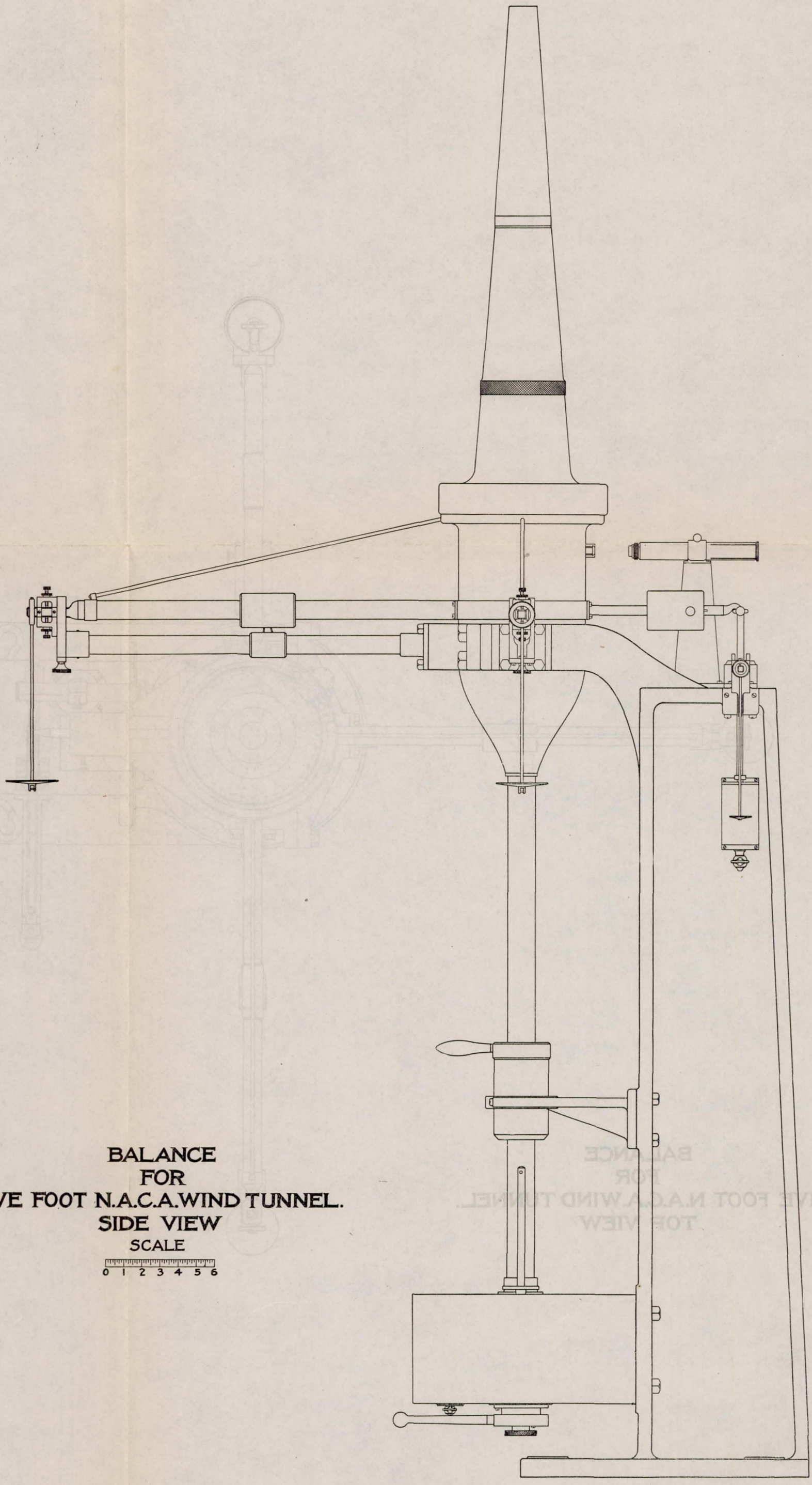
This balance is easy and quick to use, although it requires two runs to secure the lift and drag. It is hardly to be expected, however, that it can give the accuracy attainable by other methods. If the same screen is used as standard throughout a single test for wing drag, the maximum force to be measured will be more than 10 times as large as the minimum, and the inclination of the screen must accordingly vary through nearly 90°. The determination of the smallest force to within 1 per cent would necessitate the division of the scale into 1, 000 parts, and the reading of divisions so fine as these would be exceedingly difficult, especially as the pointer is certain to move slightly, pulsations in velocity of the wind not affecting the wing and the screen at the same time.

The linkage on a tunnel of this type may be placed either inside or outside the tunnel. In the first case the linkage interferes seriously with the flow around the model. In the second case the force on the model, acting out of the plane of the linkage, produces torsion in the links and greatly augments the friction at the joints.

Great care is necessary in aligning the linkage with the wind, the errors due to a fraction of a degree of misalignment being as serious as in the N. P. L. balance. There are nine joints which come into play in the Wright balance when it is used for measuring the components of force separately. The conclusion is that, for accurate work, this balance is probably inferior to several other types, but that it would be very convenient for securing comparative results in a hurry, particularly if the wind velocity were subject to fluctuations which would make it difficult to balance the fluctuating air resistance against fixed weights in the usual way. The Wright balance is more accurate and satisfactory for measurements of L/D than for either force alone.



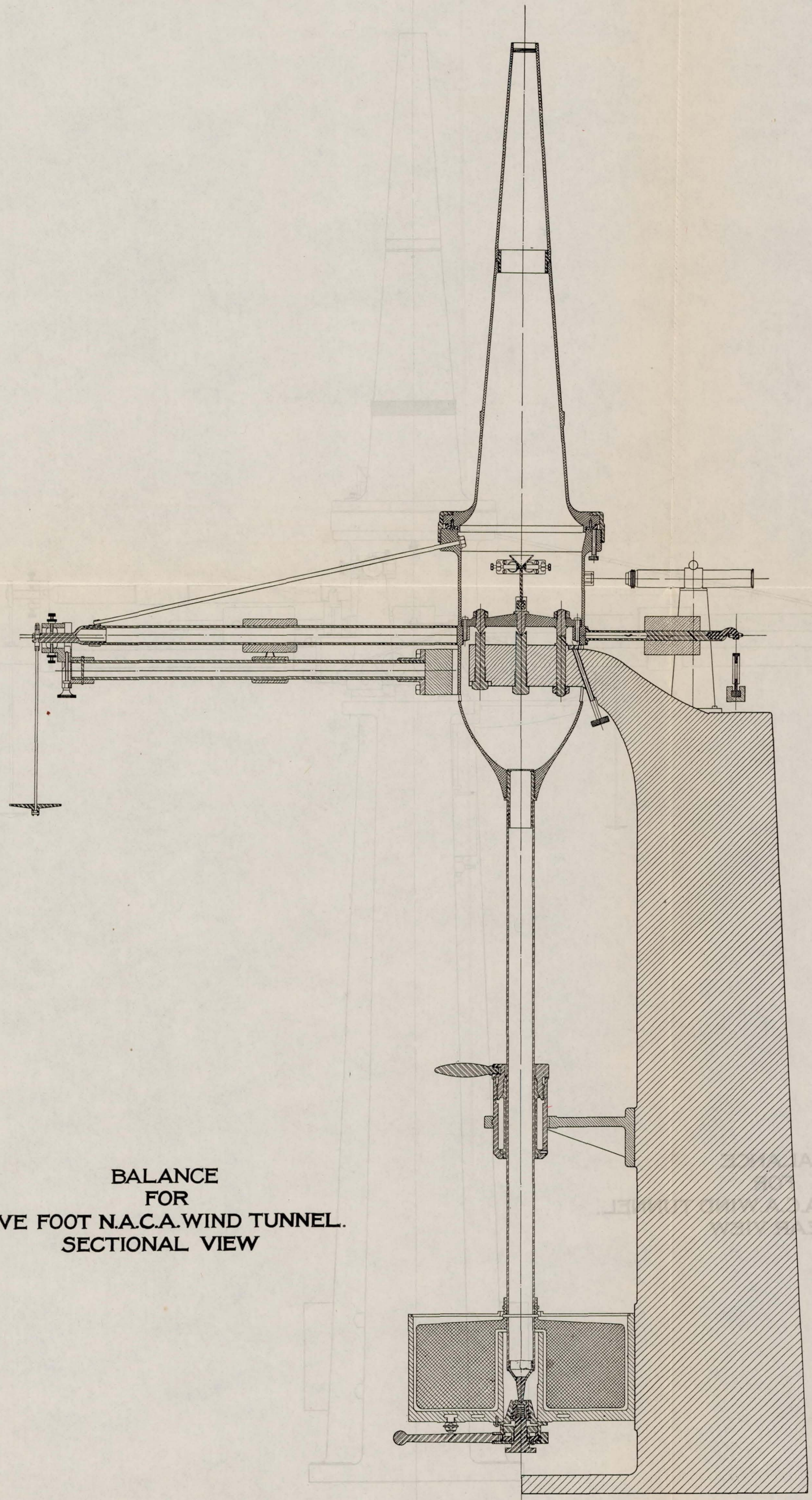
BALANCE
FOR
FIVE FOOT N.A.C.A. WIND TUNNEL.
TOP VIEW



BALANCE
FOR
FIVE FOOT N.A.C.A. WIND TUNNEL.
SIDE VIEW

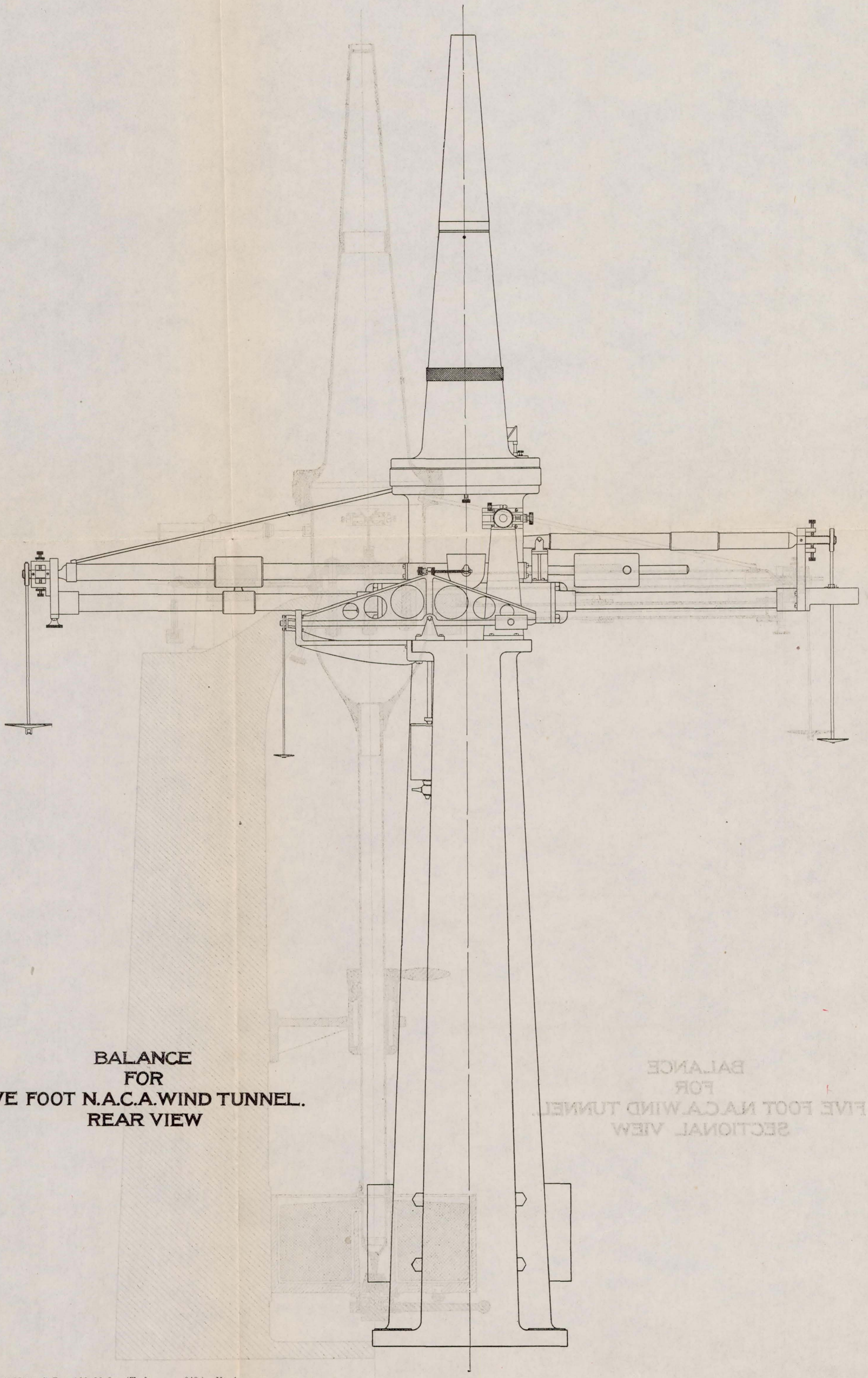
SCALE

0 1 2 3 4 5 6



BALANCE
FOR
FIVE FOOT N.A.C.A. WIND TUNNEL.
SECTIONAL VIEW

153215—S. Doc. 166, 66–2. (To face page 648.) No. 3.



BALANCE
FOR
FIVE FOOT N.A.C.A.WIND TUNNEL.
REAR VIEW

REPORT No. 73

THE DESIGN OF WIND TUNNELS AND WIND TUNNEL PROPELLERS

BY

EDWARD P. WARNER, F. H. NORTON,
and C. M. HEBBERT
Aerodynamical Laboratory, National Advisory Committee
for Aeronautics, Langley Field, Va.

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REPORT No. 73.

THE DESIGN OF WIND TUNNELS AND WIND TUNNEL PROPELLERS.

By Edward P. Warner, F. H. Norton, and C. M. Hebbert.

THE ELEMENTARY THEORY OF THE FLOW OF AIR THROUGH WIND TUNNELS.

If the air flowing through a wind tunnel and back through the room from the exit to the entrance of the tunnel followed Bernouilli's theorem with exactness, there would be no change in the energy possessed by a given particle of air, except for the loss due to friction, as the kinetic energy lost on issuing from the tunnel would be restored in the form of pressure energy. The power required to maintain the flow would then be

$$P = m \times h_f$$

where h_f is the head (in feet of air) lost by friction and m is the mass of air flowing per second. As the same mass of air must pass every point in the tunnel, the product of mean air speed by cross-section area must be a constant for its whole length, neglecting compressibility and changes in temperature during the passage. Since the major part of the frictional losses occur in the reduced section of the tunnel (provided that it is not very short and that the diffuser is not so constructed as excessively to hamper the travel of the air from the tunnel back into the room) h_f would be practically independent of the size and angle of the exit cone, and the power consumed would also be independent of these factors.

As a matter of fact the conditions of flow are not simple enough to permit the direct application of Bernouilli's theorem. Borda has shown that the loss of energy when fluid moving at high velocity in a pipe is discharged abruptly into a large room or reservoir is equal to the kinetic energy initially possessed. The kinetic energy is not converted into pressure energy as the theory indicates that it should be, and it is therefore profitable to use an exit cone of considerable length, in order that part of the kinetic energy may be saved by conversion into the potential form before the sudden discharge into the room. The length to which it is desirable to prolong the cone is limited by the growing loss by friction within the exit cone itself. A more rapid conversion of the kinetic energy by increasing the vertex angle of the exit cone is forbidden by the unwillingness of the air to change its course suddenly and follow the walls of the exit cone. If the vertex angle be made too large the effect is almost the same as that of an abrupt increase in cross section. Eiffel, as the result of an elaborate theoretical and experimental research on tunnels having exit cones generated by straight lines, has come to the conclusion that the vertex angle of the exit cone should be not more than 7°, and that the diameter at the large end of the exit cone should be three times that at the small end. It is necessary to base the dimensions of a tunnel on a compromise, as the arrangement which would give the absolute maximum of efficiency would have to be housed in a building of prohibitive size. The over all length can be materially reduced at the cost of a slight increase in power, and the first cost of the building, depending on its dimensions, must be balanced against the cost of operation, which varies with the power of the motor and so with the efficiency of the tunnel. The relations to be observed among the various dimensions of the tunnel and the angles of the cones will be discussed more fully elsewhere. Knowing the power consumed by a tunnel, its diameter, and the speed of the air, the total losses can easily be computed for that particular speed,

and the magnitude of the figure thus obtained will serve as a measure of the efficiency of operation of the tunnel. Since, however, the losses vary with the speed, they can not be compared directly for two tunnels unless they are run at the same speed. The factor most commonly used for comparisons between tunnels is the ratio of the kinetic energy possessed by the air passing through the tunnel in unit time to the work done by the motor in unit time. This is sometimes called the "over-all efficiency," but it is herein alluded to as the "energy ratio." The term efficiency in this connection is misleading, as the two quantities introduced into the ratio are not directly connected, but merely happen to have the same dimensions and so to be convenient for the purpose. Furthermore, the value of the ratio is very commonly more than 1, and is sometimes very much more.

To determine the manner in which the power consumed varies with speed, and so determine the validity or otherwise of the above relation, as well as to find the relation which must be preserved among the various factors in order that geometrically similar tunnels may be strictly comparable, the Theory of Dimensions may be used. The method pursued need not be gone into in detail, as it has been described many times before, and it will suffice to summarize the results. It appears that, if the compressibility of the air and the action of gravity on it be assumed to be of negligible importance at the speeds employed, the power consumed is proportional, for geometrically similar tunnels, to the cross-section area and to the cube of the speed, provided that $\frac{VD}{\nu}$ where V is the air speed, D the tunnel diameter, and ν the coefficient of kinematic viscosity, is maintained constant. Experiments conducted with a model tunnel at Langley Field and fully described elsewhere in this report, as well as those carried on by Durand, Castellazzi, and others, show that the "energy ratio" varies but little with changes of $\frac{VD}{\nu}$ and it is therefore safe to apply the results of model experiments to full-sized tunnels, even though the speeds may not be strictly in inverse ratio to the diameters. In general, the "energy ratio" increases as $\frac{VD}{\nu}$ increases, and it therefore requires less power to drive a tunnel than would be predicted from a direct application of the results of tests on a model of the tunnel and propeller.

The useful work done by a propeller is equal to the product of the thrust by the speed of flow of the fluid through the propeller disk. The thrust of a wind tunnel propeller is then

$$\frac{m \times h_f}{V'}$$

where V' is the speed of the air past the propeller, and this equation holds good whether Bernouilli's theorem is followed or not, so long as h_f is the total loss of head from all causes.

$$m = \frac{\rho}{g} \times A' \times V'$$

A' being the cross-section area at the propeller, and the propeller thrust is therefore equal to the weight of a column of air having a height equal to the total loss of head and a cross-sectional area equal to the disc area of the propeller. Since the power is proportional to the cube of the speed, the thrust varies as its square.

If the factors causing departures from Bernouilli's theorem are neglected, the useful work done in moving the air against friction will be, as already mentioned, independent of the degree of expansion of area in the exit cone, and so of the diameter of the propeller. Under these conditions, in fact, the advantage in respect of power consumed would rest with the short exit cone and small propeller, as the propeller efficiency is highest for a large value of the "slip function" and this is obtained by making the speed of the air through the propeller high and keeping down the diameter of the propeller. Assuming that the output of work is the same in all cases, the thrust will be inversely proportional to the speed of air through the propeller, or directly proportional to the disk area.

LAWS OF SIMILITUDE FOR WIND TUNNEL PROPELLERS.

It is obvious from a study of the Drzewiecki theory of propeller action that a series of propellers of similar blade form and width-diameter ratio, all working at the same true angle of attack, will give thrusts approximately proportional to N^2D^4, where N is the engine speed in revolutions per unit time and D the propeller diameter. This proportion can be demonstrated by the Theory of Dimensions to hold exactly true for geometrically similar propellers of perfect rigidity, but it is very nearly correct even where propellers of different pitches are concerned. It has been shown that the thrusts of a series of propellers designed to drive the same wind tunnel or geometrically similar tunnels, is proportional to N^2D^4, and also to the cross-section area, which, in turn, varies as D^2. It follows from these two relations that N^2D^2 must be a constant, and the peripheral speed of the propeller required to draw air through a wind tunnel at any particular speed will therefore be quite independent of the diameter of the propeller if the power required is independent of that diameter. It follows as an obvious corollary that, if the power required is not independent of the degree of expansion in the exit cone, the peripheral speed of the propeller will be least under the same conditions as those for which the power required has its minimum value.

It is easily demonstrable that the stresses, both those due to centrifugal force and those due to bending by the air pressure, in a series of geometrically similar propellers depend only on the peripheral speed, and that they vary as the square of that quantity. There is therefore a limiting peripheral speed which can not be exceeded with safety. For wooden propellers, it is unsafe to run the peripheral speed much beyond 60,000 feet per minute, or 305 meters per second, and it is better to stay well inside this figure. In the case of an airplane or airship where large power must be taken on a single propeller the peripheral speed can be reduced by gearing down, as the engine speed decreases more rapidly than the propeller diameter increases. In the wind tunnel, it has just been shown that this is not the case, and that the peripheral speed, and so the stress, actually increases if the propeller diameter is enlarged beyond a certain point. There is then a clearly defined upper limit to the power which it is safe to apply to driving the propeller in any given wind tunnel, and therefore a limit to the maximum speed attainable. This maximum can only be raised by reducing the losses and so improving the over-all efficiency of the plant.

Since the power required to secure a given speed with a given "energy ratio" is proportional to the cross-sectional area of the tunnel, and is also proportional to VN^2D^4, the propellers in a series of tunnels of different diameters operating at the same speed and having the same "energy ratio," all work at the same value of N^2D^2, and so of the peripheral speed. This leads to the rather astonishing conclusion that the peripheral speed necessary to produce a given air speed depends only on that air speed and on the energy ratio, and is not at all affected by the size of the tunnel or of the propeller (except indirectly, in so far as these factors have an effect on the energy ratio). For any value of the energy ratio, then, there is a limiting air speed which can not be exceeded without running the peripheral speed up beyond the limits of safety, and this speed is the same for large tunnels as for small, although the actual power consumed of course varies with the tunnel diameter. In order to realize the highest possible wind speed the power coefficient of the propeller must be made as large as possible. This can be done by using many blades and by making them of high-lift sections set at relatively large angles of attack. If the velocities desired are too high to be obtained in this way, it will be necessary to use two or more propellers arranged in tandem, acting like a multi-stage compressor.

It has been shown that

$$P = K_1 D_1^2 V_1^3$$

and also that

$$P = K_2 V_2 N^2 D_2^4$$

where the subscripts 1 and 2 denote, respectively, the conditions existing in the experimental chamber and at the propeller, and K_1 and K_2 are experimental constants depending on the

type of tunnel and propeller. Since $D_1^2 V_1 = D_2^2 V_2$, if the velocity across the exit cone at the propeller is uniform, the first of these relations may be written

$$P = K_1 D_2^2 V_2 V_1^2.$$

Dividing this by the second of the relations above,

$$K_2 N^2 D_2^2 = K_1 V_1^2$$

and

$$\frac{V_1}{ND_2} = \sqrt{\frac{K_2}{K_1}}.$$

The ratio of the air speed to the peripheral speed is thus a constant for a given tunnel, and its value for any particular tunnel depends only on the type of installation—not at all on its size.

Values of $\frac{V_1}{ND_2}$ for a few tunnels are tabulated herewith:

Name.	V_1(m./sec.).	N (r. p. s.).	D_2(m).	$\frac{V_1}{ND_2}$.
Eiffel, Auteuil	31.8	3.83	3.80	2.18
Leland Stanford, Jr.	24.0	6.77	3.35	1.06
Langley Field, model	41.5	68.3	0.610	1.00
N. P. L., 4-foot	15.24	22.5	[1] 1.676	0.40
Curtiss, 4-foot	34.5	22.92	2.44	0.62
Curtiss, 7-foot	42.8	20.00	3.66	0.58
McCook Field	221.0	29.50	1.52	4.92

[1] This tunnel was square and the ratio of V_1 to V_2 is therefore equal to the ratio of the cross-section areas and not to that of the squares of diameters at the minimum section and at the propeller.

Castellazzi's experiments.

Number of blades.	Blade width, diameter.	V_1(m./sec.).	N(r. p. s.).	D_2(m).	$\frac{V_1}{ND_2}$.
24	0.0435	25.0	17.25	0.600	2.41
24	.0300	25.0	19.17	.600	2.17
16	.0650	25.0	16.67	.600	2.50
12	.0435	25.0	20.50	.600	2.03
8	.0650	25.0	19.33	.600	2.15
6	.0650	25.0	22.17	.600	1.88

It will be noted that the highest value of $\frac{V_1}{ND_2}$ in this table, with one exception, is 2.50, and this value was obtained in a tunnel of very efficient type in combination with a propeller having a total blade width equal to one-third of its circumference. Analysis by the Drzewiecki method leads to the belief that it will be possible to raise $\frac{V_1}{ND_2}$ to 3, but that this figure can hardly be exceeded with propellers resembling those now in use. The exception mentioned above, the small tunnel at McCook Field, has a fan of special type and will be discussed later.

If the allowable peripheral speed be taken as 285 meters per second, ND_2 is 90.6 meters per second. If $\frac{V_1}{ND_2}$ be assumed to be 3 the limiting value for V is 271.8 meters per second, or 607 miles an hour. This is a considerably higher speed than has yet been attained, or than is ever likely to be desired in connection with the study of aircraft. If higher speeds should be needed they can be secured either by the use of a multiplicity of propellers in series or, up to a certain point, by the use of a fan with an abnormally large hub and short blades entirely filling the periphery of the hub, as in the McCook Field tunnel,[1] where the hub diameter is

[1] Studies in high speed aerodynamic phenomena, by F. W. Caldwell and E. N. Fales; Automotive Industries, Aug. 28, 1919, p. 422.

two-thirds of the total diameter. If $\frac{V_1}{ND_2}$ is raised to 5, a value only a little higher than that in the McCook Field tunnel, the limiting air speed for the peripheral speed given above is increased to 453 meters per second, or 1,012 miles an hour.[1]

The assumption has so far been made that the air has a free passage across the whole area swept by the propeller. Of course the hub always blocks off a part of this area, but it has usually been an insignificant fraction. If the propeller diameter is n times the hub diameter, the proportion of the area blocked off is $\frac{1}{n^2}$, and the speed of the air across the propeller blades, assuming a uniform distribution everywhere outside the hub, is increased in the ratio $\frac{1}{1-\frac{1}{n^2}}$. If the propeller be made, as is the common practice, with a constant blade width, and if the lift coefficient be assumed constant all along the blade, the portion of the total thrust given by the part of the blade inside of any given point is very nearly proportional to the cube of the radius at that point. For example, one-eighth of the thrust would be given by the inner half of the blades if they extended clear to the center, with no hub at all. The use of a hub, or the covering up of part of the blades with a "spinner" therefore decreases the thrust in the ratio $1-\frac{1}{n^3}$. Since useful power is equal to the product of the thrust by the speed across the propeller disk, the net change in power, due to hub or spinner, is

$$\frac{1-\frac{1}{n^3}}{1-\frac{1}{n^2}}=\frac{n^3-1}{n^3-n}=1+\frac{1}{n^2+n}.$$

The increase in power coefficient by the use of a spinner, the propeller pitch being adjusted to give the same angle of attack of the blades with as without the spinner, is 5 per cent for a spinner or hub one-quarter the diameter of the propeller, 17 per cent when the ratio is one-half, and 27 per cent when, as in the McCook Field tunnel, it is two-thirds. Furthermore, the use of a very large hub makes it possible to use more blades and make their total width a larger fraction of the circumference of the circle swept by the blades. In the McCook Field fan there are 24 blades, and their total width is approximately equal to the circumference of the hub.

Where very high speeds are desired, as in the calibration of air-speed meters, a throttling insert has sometimes been used to reduce the section of a large tunnel. The effect is to increase the speed, but usually much less than is expected. If the "energy ratio" remained constant, halving the diameter of the tunnel would increase the speed available with a given expenditure of power by 59 per cent. A change of this sort usually, however, diminishes the energy ratio unless the tunnel is of the type combining a long straight portion with conical ends, and permitting of the extension of the cones back into the straight cylindrical part. The use of a throttling insert in a tunnel with a short experimental chamber, like those used by Eiffel and Crocco, is almost certain to lead to a large drop in energy ratio, and the increase of speed by halving the diameter in such a laboratory would probably be less that 50 per cent. Furthermore, it is necessary for best results that the propeller ordinarily used be replaced by one especially designed for use in conjunction with the throttling insert. If the diameter of the tunnel be halved the area at the smallest section is divided by four, and, even with an increase of 59 per cent in speed at the throat or in the experimental chamber, the speed of the air past the propeller is reduced by 60 per cent. Since the propeller diameter and its normal rotational speed to develop the rated power are unchanged, the propeller for use with the throttling insert must have a much smaller effective pitch than that employed with the full section, if the maximum of efficiency is to be obtained.

[1] In this analysis the change of density of the air, due to decrease of static pressure with increasing speed, is neglected. This does not lead to a very large error, as both the propeller thrust and the frictional resistance to the passage of the air increase with the air density, the former varying more rapidly than the latter.

RELATIVE ADVANTAGE OF SMALL AND LARGE TUNNELS.

It has just been shown that the gain in speed by reducing the diameter by the use of a throttling insert is disappointingly small. This leads naturally to a study of the best size of wind tunnel to be employed, and of the relation between speed and size which should be sought.

In the construction of aerodynamical laboratories, as the attempt has been made to approach ever more nearly to full-flight conditions, two divergent schools of practice have grown up. The first, best represented by the National Physical Laboratory in England, has constantly increased the diameter of the wind stream, and so increased the size of model which may be tested, but has remained content with relatively moderate wind speeds. The second, on the other hand, has concentrated its efforts on the pumping of the air across a small section at enormous velocity.

In comparing the merits of the high speed and the large diameter tunnels, there are three points which must be borne in mind. In the first place, the highest possible value of LV (LV being the criterion of dynamic similarity) is to be obtained with a minimum expenditure of power. Secondly, the interference between the model and its support is to be reduced to a minimum, and, finally, that disposition should be favored which enables us to secure the greatest accuracy in the construction of the models.

It has been shown that

$$P = KA V^3 = K_1 D^2 V^3$$

where D is the diameter of the tunnel and K_1 is a constant.

In order to avoid interference between the model and the walls of the tunnel, the ratio of maximum span to tunnel diameter must not exceed a certain value (usually about 0.4). Setting L, the span of the model, proportional to D, we can then modify the above equation:

$$P = K_2 L^2 V^3 = K_3 \frac{(LV)^3}{D}.$$

The power required to drive the fan will therefore be least, for any given value of LV, in that tunnel where the diameter is largest and the speed is smallest.

The relative magnitude of the interference between the model and its support, the so-called "spindle effect" depends on the ratio of the spindle diameter to the linear dimensions of the model. Its reduction is a matter of very vital importance, the spindle correction undoubtedly being the largest single source of error in most wind-tunnel tests.

The bending moment in the spindle at any point (say one chord length from the wing tip) is proportional to the product of the span by the force acting on the model.

$$M = C_1 LF = C_2 L(L^2 V^2) = C_2 L^3 V^2.$$

If d is the diameter of the spindle, the relations between bending moment, fiber stress, and deflection may be written:

$$f = \frac{Mc}{I} = \frac{C_3 L^3 V^2}{d^3}$$

$$y = \frac{ML^2}{C_4 EI} = \frac{C_5 L^5 V^2}{d^4},$$

if the material of the spindle be the same in all cases.

If the maximum fiber stress be limited to a definite value,

$$\left(\frac{d}{L}\right)^3 = \frac{C_3 V^2}{f}$$

$$\frac{d}{L} = \left(\frac{C_3}{f}\right)^{\frac{1}{3}} \times V^{\frac{2}{3}}.$$

The ratio of spindle diameter to model size, and consequently the spindle interference, will therefore be greatest in the high-speed, small, diameter tunnel.

If, as is usually the case, it is stiffness and not strength which prescribes the diameter of the spindle,[1] and if the deflection be limited to a determined value, the required spindle size is given by the equation:

$$\left(\frac{d}{L}\right)^4 = \frac{C_5 L V^2}{y}$$

$$\frac{L}{d} = C_6 \times (LV)^{\frac{1}{4}} \times V^{\frac{1}{4}}.$$

For a given value of LV, then, $\frac{d}{L}$ will be least when the speed is low and the tunnel diameter large. The advantage of the large tunnel on this score is even greater than appears at first, as a larger spindle deflection is permissible with a large tunnel than with a small one. In fact, the permissible deflection increases nearly as rapidly as does the tunnel diameter.

In respect of the third consideration, accuracy of construction of the model, the superiority of the large tunnel, permitting the use of a large model, is so manifest as hardly to call for discussion. A model of 3-foot span can include many parts, such as fittings and wires, which it is quite hopeless to put on one of half that size.

So far, the advantage has rested with the large diameter in every particular. It has one disadvantage in that the size and weight of the balance are much increased, longer weighing arms, heavier counterweights, and a general strengthening up of the apparatus are necessitated. Furthermore, the initial cost of the building to house a large tunnel is very high. In the writer's opinion, however, the advantages far outweigh the drawbacks, and any future development of wind tunnels for model testing should proceed along the lines of increasing the diameter rather than the speed.

All that has been said against high speeds applies, of course, only to tunnels for the testing of models. Speeds equal to the speeds of flight of airplanes are essential for the calibration of instruments.

DESIGN OF WIND TUNNEL PROPELLERS BY THE DRZEWIECKI THEORY.

It is possible, if the rate of flow of the air through a wind-tunnel propeller be known, to predict the performance of the propeller by the Drzewiecki theory. Indeed, the application of that theory to wind-tunnel propellers is rather simpler than its application to the airplane, as there is no in-draught correction to contend with. If the velocity at the minimum section of the tunnel is given, the velocity through the propeller can be computed with absolute accuracy on the assumption that the distribution across the exit cone is uniform. This assumption can only justify itself in the results of the analysis derived from it as a basis.

The best way of checking the accuracy of the analytical method of design is to apply it to a propeller already working satisfactorily. This has been done with the propeller used in the model wind-tunnel experiments described in a later section of the report. The angle of the relative wind to the plane of the propeller can be computed from the wind speed, and it is then possible, knowing the angles of blade setting, to work back and find the angle of attack of each blade element. Having this, the power consumed by the propeller and its efficiency can be found in the usual way. This was done for two cases. In the first case the tunnel was of the Eiffel type, with an enlarged experimental chamber, and the calculated power checked the actual consumption within the experimental error (about 2 per cent, owing to uncertainty as to motor losses). In the second case the air stream was inclosed throughout, a cylindrical tube being carried across the experimental chamber, and the power consumed was about 15 per cent more than that calculated. It is considered that both of these tests showed a very fair check and that the use of the Drzewiecki theory for design is amply justified. The average error, both in these and in other cases which have been tried, is in the direction of underestimation of the power consumption.

[1] The effect of spindle deflection on the accuracy of measurements is discussed in Report No. 72, on Wind Tunnel Balances.

In designing a propeller for a new tunnel it is necessary to make an estimate of the energy ratio, and so of the speed for a given power. If the estimate is too low, the propeller pitch will be made too low, and the propeller will work at an inefficiently small angle of attack. The speed will be higher than that estimated, but still not so high as it would be with a proper propeller. If the propeller blades are made too narrow, or if too few blades are used, the full power of the motor will not be absorbed at the rated revolutions per minute. The speed will then fail to reach the value expected for the rotational speed realized, the angle of the relative wind to the plane of the propeller will fall below the estimated value, and the angle of attack of the blade elements will become inefficiently large. Any change of this sort from the designed conditions of operation tends to correct itself, as the larger angle of attack increases the power consumed and the thrust given by the propeller. This in turn speeds up the air and brings the angle of attack to a lower value. It is for this reason that fairly satisfactory results have so frequently been secured with propellers chosen almost at random, but the best efficiencies can only be obtained with a propeller designed especially for the conditions under which it is to operate. The commonest faults in the design of wind-tunnel propellers have been either to overestimate the energy ratio for a projected tunnel or to underestimate the total blade width required for the absorption of the given power at the most efficient angle of attack. The result in both cases is to cause the blades to work at too large an angle of attack.

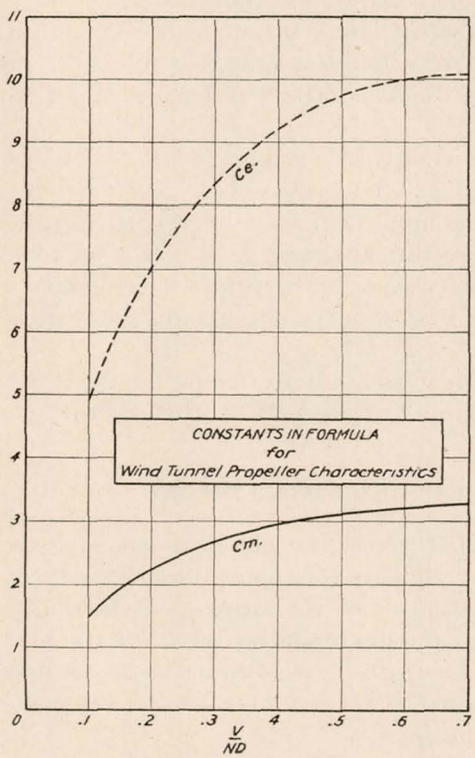


FIG. 1.

There is some doubt as to the manner in which the angle of attack should vary along the blades. Most wind-tunnel propellers in which the Drzewiecki system was used at all have been designed for a constant angle of attack, but since, as was just noted, the propellers have usually been made too small to absorb the full power of the motor, they actually work at an angle of attack larger than that desired and increasing from the tip to the root of the blade. In the design of a propeller for the Langley Field wind tunnel the opposite disposition has been deliberately chosen, the angle of attack being made largest near the tips and decreased toward the hub in order that the air may be drawn out along the sides of the exit cone and in order that the larger part of the thrust may come on the most efficient portion of the blades. No experimental data on the effect of this arrangement of the blade sections are available as yet.

In order to make it easy to estimate the number of blades and the blade width required in a propeller for a tunnel, assuming that the wind speed, power consumption, and revolutions per minute are known, a number of propellers have been computed for a variety of conditions and the results expressed by a formula and a curve. The power is given by the formula

$$P=\frac{V\times b\times D^3\times N^2\times n}{C\times 10^8}$$

where P is the horsepower input of the motor, V the air-speed through the propeller in meters per second b the blade width in centimeters, N the revolutions per minute, n the number of blades, D the propeller diameter in meters, and C a constant, the magnitude of which depends on the pitch of the propeller. C is plotted against $\frac{V_2}{ND_2}$ in figure 1. If English units be used,

V being given in miles an hour, D in feet, and b in inches, a factor 10^9 replaces 10^8 in the denominator of the power formula given above, and C is given by the dotted curve in figure 1. The theoretical basis for the derivation of this formula is the same as that for a formula derived by the writer, and previously published,[1] for the power consumption of airplane and airship propellers.

The efficiency of wind-tunnel propellers is usually very low, and the maximum attainable depends largely on the magnitude of the pitch ratio. In the propeller designed for the Langley Field tunnel the calculated efficiency is 58 per cent. In figure 2, probable propeller efficiencies have been plotted against $\frac{V_2}{ND_2}$. The efficiencies there predicted may be exceeded when the peripheral speed is low, so that thin sections can be used over the whole length of the blade, or when a very large hub or spinner is used to cover up the less efficient parts. In order to give an idea of the range of values of $\frac{V_2}{ND_2}$ employed in successful tunnels, a few are tabulated below, the data being taken from the table under "Laws of Similitude for Wind Tunnel Propellers".

	$\frac{V_2}{D_2}$
Leland Stanford, Jr.	0 265
N. P. L., 4-foot	.27
Curtiss, 4-foot	.20
Curtiss, 7-foot	.20
Langley Field model	.25
McCook Field	.48

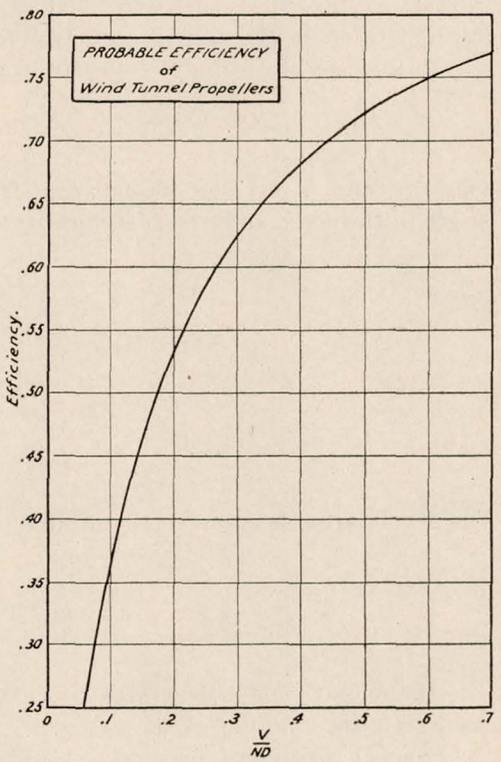


FIG. 2.

THE FORMS OF ENTRANCE AND EXIT CONES.

There has been a great deal of discussion and dispute as to the best form for the cones in which the air acquires and loses its speed, and further experiment is desirable. The effect which changes in the form of these cones have on the efficiency is, however, much less than has commonly been supposed, judging from experiments recently performed at Langley Field and reported in another part of this paper.

In the absence of data to indicate the best form, most of the wind tunnels which have been constructed have used, at least on the exit side of the experimental chamber, the frustrum of a right cone generated by a straight line. This was true of the N. P. L. and all their imitators, and it has been true also of most of the tunnels designed with an eye to the results of the experiments of Crocco and Castellazzi, and using long exit cones of very gradual slope. A surface of this type has at least the advantage of being easy to generate and to fabricate from wood or sheet metal. There is, however, no particular reason to believe that it is the most efficient that can be constructed from an aerodynamical point of view. Eiffel and his followers, on the other hand, have always used cones of curving form. It seems fair to assume that the loss in diverging nozzle is partially dependent on the deceleration of the fluid, and that the loss will usually be least where the deceleration is least. It is obvious, furthermore, that the flow through the exit cone will be smoothest and least turbulent when the form of the cone is smooth, and that any abrupt change of slope of the walls, such as that at the juncture of the parallel portion of the tunnel with an exit cone generated by a straight line, is liable to cause the lines of flow to break away from the contour of the tunnel wall, and to establish a region of "dead-water"

[1] Aviation and Aeronautical Engineering, Feb. 15, 1919, p. 84.

and turbulence around the periphery of the exit cone. The smoothness of a curve can best be judged by taking differences or, if the equation of the curve is known, by plotting the derivatives. This was done in designing the cones for the Leland Stanford, Jr., tunnel.[1] The plotting of the curve of acceleration for a tunnel will then serve the double purpose of indicating the smoothness of the curve and of giving the maximum rate at which the velocity of the air is changing, and so the maximum force necessary for accelerating the moving stream.

A curve of velocity against distance along the axis of the tunnel can be drawn on the assumption that velocity is inversely proportional to the square of the diameter of the tunnel. This, of course, is true only for velocity parallel to the axis, and entirely neglects the radial component. In order to obtain the acceleration from this curve, the derivative giving acceleration is written

$$\frac{dv}{dt}=\frac{dv}{dx}\times\frac{dx}{dt}=v\times\frac{dv}{dx}$$

The acceleration at any point along the tunnel is therefore equal to the product of the ordinate of the curve just described by its slope at that point. These factors can be found graphically or, in the case of a curve for which the equation is known, analytically.

In the case of a straight cone, for example, the formula for diameter at any point is

$$D=D_1+(D_2-D_1)\times\frac{x}{l}$$

where D_1 and D_2 are the diameters at the small and large ends of the cone, respectively, l the length of the cone, and x the distance from the small end. Then

$$v=v_1\times\frac{D_1^2}{D^2}=v_1\times\frac{D_1^2}{\left[D_1+\frac{x}{l}(D_2-D_1)\right]^2}$$

and

$$\frac{dv}{dx}=\frac{-2v_1\times D_1^2\times\frac{D_2-D_1}{l}}{\left[D_1+\frac{x}{l}\times(D_2-D_1)\right]^3}$$

The acceleration is equal to the product of these expressions, or

$$\frac{dv}{dt}=\frac{-2v_1^2\times D_1^4\times(D_2-D_1)}{l\times\left[D_1+\frac{x}{l}\times(D_2-D_1)\right]^5}$$

If the exit cone is generated by rotating about the axis of the tunnel a parabola having its vertex at the junction of the exit cone with the straight portion the formula for diameter of the cone at any point becomes

$$D=D_1+\left(\frac{x}{l}\right)^2\times(D_2-D_1)$$

The acceleration may then be obtained by the same steps just employed for the straight cone.

$$v=v_1\times\frac{D_1^2}{\left[D_1+\left(\frac{x}{l}\right)^2\times(D_2-D_1)\right]^2}$$

$$\frac{dv}{dx}=-2v_1\times\frac{D_1^2}{l^2}\times\frac{2x\times(D_2-D_1)}{\left[D_1+\left(\frac{x}{l}\right)^2\times(D_2-D_1)\right]^3}$$

$$\frac{dv}{dt}=\frac{-4v_1^2\times D_1^4\times x\times(D_2-D_1)}{l^2\times\left[D_1+\left(\frac{x}{l}\right)^2\times(D_2-D_1)\right]^5}.$$

[1] Third Annual Report of the National Advisory Committee for Aeronautics, p. 87, Washington, 1918.

In figure 3, the velocity and acceleration, as well as the cone diameter, are plotted against x for cones of these two forms. The units are meters and seconds, and the curves relate to a tunnel having an exit cone tapering in diameter from 1.5 meters to 3 meters in a length of 6 meters, and a wind speed of 50 meters per second. It appears that the straight cone is far inferior, judged by the criteria laid down above, to that of parabolic form. The maximum acceleration for the first is more than two and a half times that for the second, and there is a large discontinuity in the acceleration curve for the straight cone, as might be anticipated from the discontinuity in the slope of the sides of the tunnel. The parabolic form gives zero acceleration at the juncture of the exit cone with the experimental chamber, and this is very desirable, but it does not give a zero acceleration at the point where the air emerges from the exit cone. There is some question as to the desirability of using a reverse curve which will have tangents parallel to the axis of the tunnel at both its ends, and so securing zero acceleration at both ends of the exit cone. The air has to be slowed down some time, and there would seem to be little advantage in bringing it to a constant velocity as it leaves the retaining walls of the exit cone if it is to be decelerated again the instant that it is free from those walls. Also, the current of air, since it is to be turned through an angle of 180° and travel back through the room to the entrance of the tunnel, must acquire a radial velocity either inside the exit cone or immediately after it has left it. No gain is apparent from a construction which permits the air to acquire a certain amount of radial velocity and then straightens it out again, only to force it to turn outwards once more a few feet farther along its path. The effect of a reversal in the curve of the walls near the large end of the exit cone is certainly slight, as very good results have been obtained both with and without such a reversal.

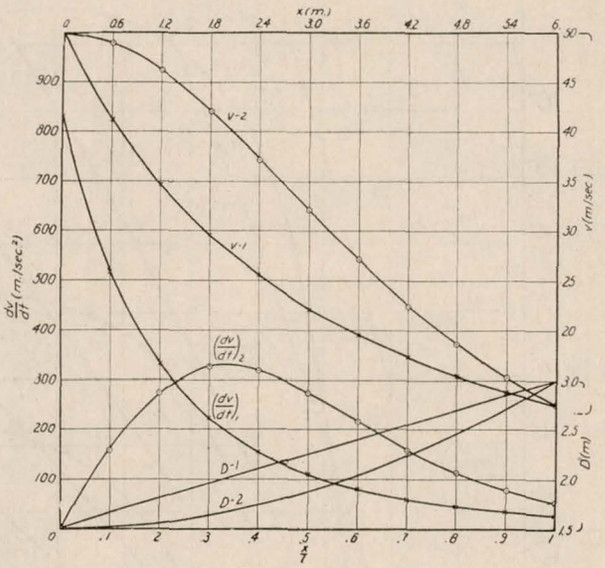


FIG. 3.—Velocities and accelerations of fluid in exit cones.

The form of the entrance cone appears to have but little effect on the "energy ratio," and this is in accord with the results of hydraulic experiments, where it is always found that the loss

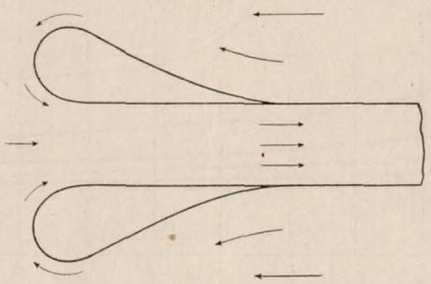


FIG. 4.—Fairing of entrance to N. P. L. tunnel.

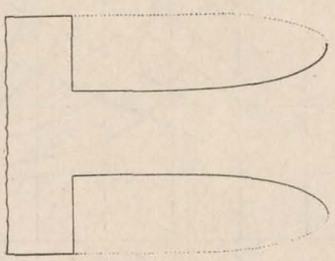


FIG. 5.—Proposed fairing of entrance cone.

in a converging nozzle is much less than that in a diverging one, and that the nozzle can converge very abruptly without seriously increasing the loss. Most of the European experiments on model tunnels have been made with straight entrance cones. While these are probably as efficient as any other type, they must have a vena contracta near the large end, causing turbulence which persists into the experimental chamber, and there is further eddying and disturbance due to the turning of the air around a sharp corner at the small end of the cone. To avoid

these difficulties and to secure as steady a flow as possible in the experimental chamber it is the almost universal practice, in actual tunnels, to make the entrance cone of curving form. It has been found at the National Physical Laboratory that, even if the entrance cone, or bell-mouth, as it is called there, is curved around until a tangent to the wall at the large end is perpendicular to the axis of the tunnel, there still are marked and persistent eddies in the neighbor-

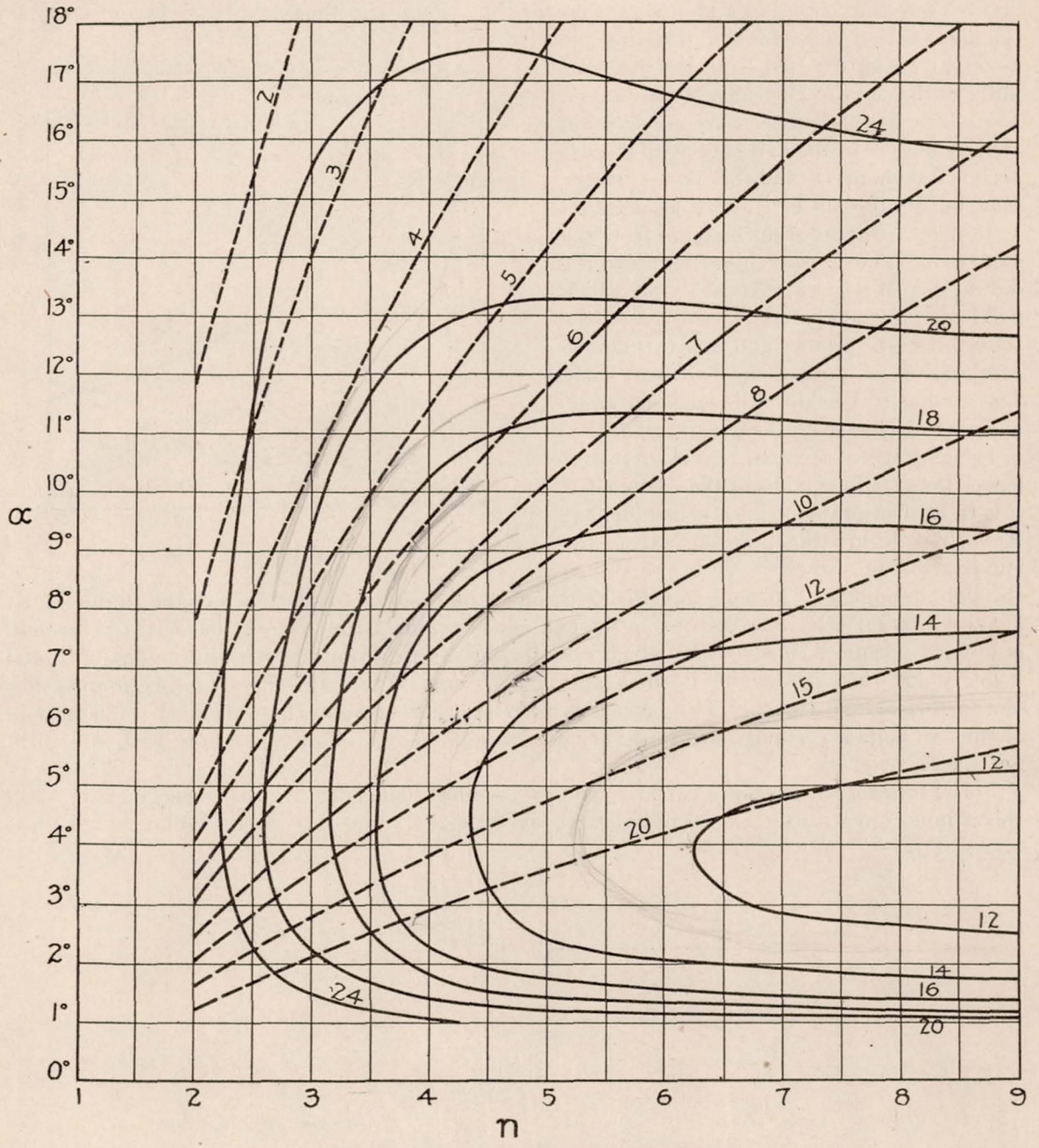


FIG. 6.—Percentage losses in exit cones of various forms.

hood of the sharp edge. To entirely eliminate this edge it is now the practice at the N. P. L. to carry the bell-mouth around, as shown in figure 4, until it meets the straight portion of the tunnel. This method has not been adopted at Langley Field, as it is desired to make some experiments on the full-sized tunnel with the normal entrance cone, but provision has been made for building a fairing to extend clear around to the experimental chamber, as shown by the dotted lines in figure 5, so giving the air a perfectly smooth passage.

THE THEORY OF LOSSES IN THE EXIT CONE.

The losses in the exit cone of a wind tunnel arise from three sources. The first is the friction against the walls, and is best determined by Fritzsche's formula for fluid friction. The second is the diverging angle of the cone, which, as already noted, always leads to a loss of energy as compared with the ideal conditions expressed by Bernouilli's theorem. The magnitude of this loss is determined with satisfactory accuracy by a formula devised by Fliegner. Finally, there is a loss due to the sudden release of the air from the exit cone and its passage into the room, where its velocity drops almost to zero. This loss was shown by Borda to be equal to the kinetic energy possessed by the air at the large end of the cone. These losses, and their relation to the factors entering into wind tunnel design, together with all the losses in other parts of the tunnel, have been fully discussed by Eiffel,[1] and it is not necessary to repeat his work here. For the benefit of those designing tunnels, however, a set of curves has been plotted which make it possible to read off at once the loss in a straight conical exit cone of any type and to determine, given the limiting conditions, such as size of building to house the tunnel, the characteristics of the best exit cone for that particular case. Since from 80 per cent to 90 per cent of the total losses in a tunnel (not including those in the propeller) occur in the exit cone the problem of designing a tunnel with a high energy ratio is essentially a problem of reducing the losses in the exit cone.

In figure 6 the ordinates are the vertex angles of exit cones, the abscissae the ratio of the cross-section area at the large end of the cone to the cross-section area where models are tested, at the throat or in the experimental chamber. The family of curves drawn in full lines are curves of equal loss, and the number which each one bears expresses the loss in the exit cone as a percentage of the kinetic energy possessed by the air at the smallest section of the tunnel. For example, if there were no losses except those in the exit cone, a tunnel having an exit cone of form corresponding to any point on the curve marked 20 would have an energy ratio of 5. The nearly straight dotted lines running across the sheet diagonally correspond to various constant lengths of exit cone, and they are marked with the ratio of length to diameter at the small end.

To illustrate the use of this chart in choosing an exit cone a few illustrative examples will be given.

1. A tunnel is to be 2 meters in diameter. In order to keep the size and cost of the building within reasonable limits, it is desired that the length of the exit cone shall not exceed 20 meters. Subject to this limitation, the cone is to be chosen for maximum efficiency.

The ratio of length to diameter here is 10. Passing along the dotted line bearing that number, it is seen that it cuts the curve of 16 per cent loss at two points and that it does not cut the 14 per cent curve at all, but that it approaches nearest to the latter at the point ($\alpha=6.8°$, $n=4.8$). It is usually best to make n a little smaller than the value for minimum loss in the exit cone, as a reduction in n is a reduction in the diameter at the large end of the cone and so in the propeller diameter, and it has already been shown that this is favorable to propeller efficiency. It would probably be best, in this case, to take $n=4.3$, $\alpha=6.1°$, or some other combination in that immediate neighborhood.

2. A very large tunnel is to be built, and, in order that the propeller diameter may not be unreasonably large, as well as to keep down the height of the building, the propeller diameter is limited to twice the diameter of the tunnel at the minimum section.

If the ratio of diameters at the ends of the exit cone is 2, $n=4$. Drawing a vertical from the scale of abscissæ at this point, it is seen that it approaches nearest to the 14 per cent curve at ($\alpha=4.5°$). The length of the exit cone for this angle is 13 times the minimum diameter. It would not be advisable, under these conditions, to choose the cone for the absolute maximum of efficiency, as the length could be decreased 4½ diameters at a cost of only 5 per cent increase in the total power by increasing α to 6.7°. Since the curvature of the constant

[1] Note on the Calculation of the Efficiency Coefficients of Air Channels, G. Eiffel, Paris, 1918.

power curves is not abrupt the conditions can be changed considerably from those for minimum loss without very much affecting the efficiency, and it is almost always worth while to make some concession of efficiency in order to reduce the dimensions of the building and of the tunnel itself.

EXPERIMENTS ON MODEL WIND TUNNELS.

The first set of experiments conducted dealt with a model of the wind tunnel for Langley Field, as it was originally planned. The tunnel was of the Eiffel type, with a large experimental chamber, and this chamber was reproduced to the proper scale in the model. All of the models used were one-fifth the size of the large tunnel, the experimental chamber being 30.5 cm. in diameter in the models. The entrance and exit cones were made of plaster over a base of wallboard, and were shellaced, so that a very smooth surface was secured. The plaster was scraped to form, as soon as it is set, with a steel template rotated about a shaft running along the axis of the tunnel. An exit cone is shown, with the template in place and ready to apply the plaster, in figure 7. The drive was by belt from a 2-horsepower induction motor, and the propeller was four-bladed. The blades had a constant width of 4.5 cm. The speed of the propeller was measured with a Veeder liquid tachometer, and the power consumption with a polyphase wattmeter. The tunnel and instruments ready for use are shown from two points of view in figures 8 and 9, the propeller in figure 10. Figure 11 illustrates the Pitot tube used for measuring the wind speed. A hole 1 mm. in diameter is bored in the tapering end, and communicates with one of the two hypodermic tubes passing down the shank. The static pressure is secured inside a hole 2.5 mm. in diameter drilled from the other end of the tube, and this hole communicates with the other hypodermic tube. The piece between the two hypodermic tubes is a solid rod to provide stiffness. Since the static pressure aperture points to the rear, the pressure in that side of the gauge is less than the true static, and the readings are higher than they theoretically should be. The tube was calibrated against a standard Pitot in the wind tunnel of the Bureau of Standards, and was found to have a constant of 1.167 (i. e., the readings of the small Pitot tube were 16.7 per cent higher than they theoretically should have been). This Pitot tube was very insensitive to rotations in all planes, as it could be turned 20° without affecting the reading more than 8 per cent. This is a great advantage where, as in traversing the cones, the direction of flow of the air is uncertain. The dynamic head on the Pitot tube was measured by an alcohol gauge, shown in figure 12. Only one side of the gauge is ordinarily used. Since the glass tube is raised and lowered by a micrometer screw so that the meniscus of the alcohol stands opposite the same mark on the tube for each reading there are no corrections, such as are required in the ordinary Krell manometer, for varying diameter of the glass tube or for changing level of the fluid in the reservoir.

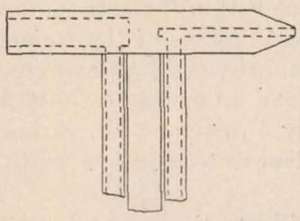


FIG. 11.—Pilot tube used in experiments with model tunnels.

The mode of procedure in each complete test was to make traverses of the entrance and exit cones and the experimental chamber at several points, measuring the wind speed at several radii, and then to make runs at a number of different speeds, measuring the wind speed at the point where a model would be placed for test and the power consumption. The energy ratio and the manner of its variation with speed was determined from this set of runs.

The traverses for the original model are plotted in figure 13. The points A and B were in the entrance cone, A being at the large end of the cone, B midway between the ends. C was in the experimental chamber, 5 cm. from the entrance cone side. D was 20 cm. downstream from the entrance cone and E was 46 cm. from the entrance cone, 15 cm. from the exit. F, G, and H were in the exit cone, and were equally spaced along its length, H being in front of the propeller and as close as it could be placed without danger of having the tube struck by the blades. The exit cone in this model was parabolic in form. The location of the point D corresponded to that at which the model is to be placed in the full-sized tunnel.

The speed in the entrance cone had a maximum at the center and one near the wall, the one near the wall being higher than that in the center. The maximum occurred within 2 cm.

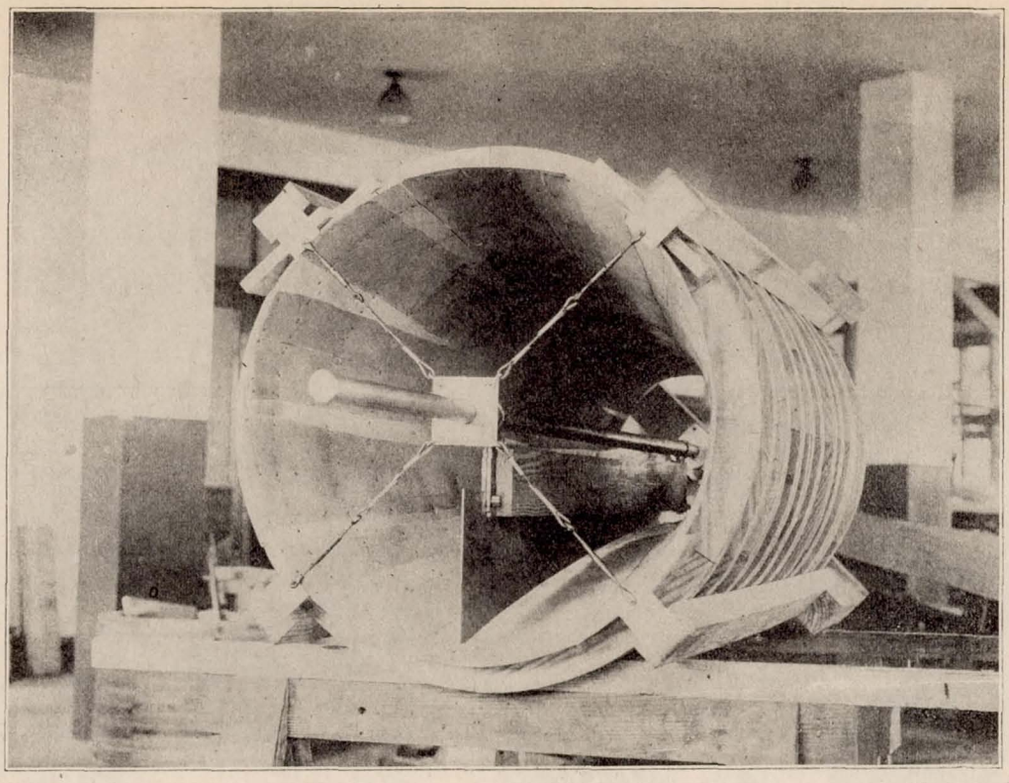


FIG. 7.—METHOD OF CONSTRUCTING PLASTER CONES FOR MODEL TUNNEL.

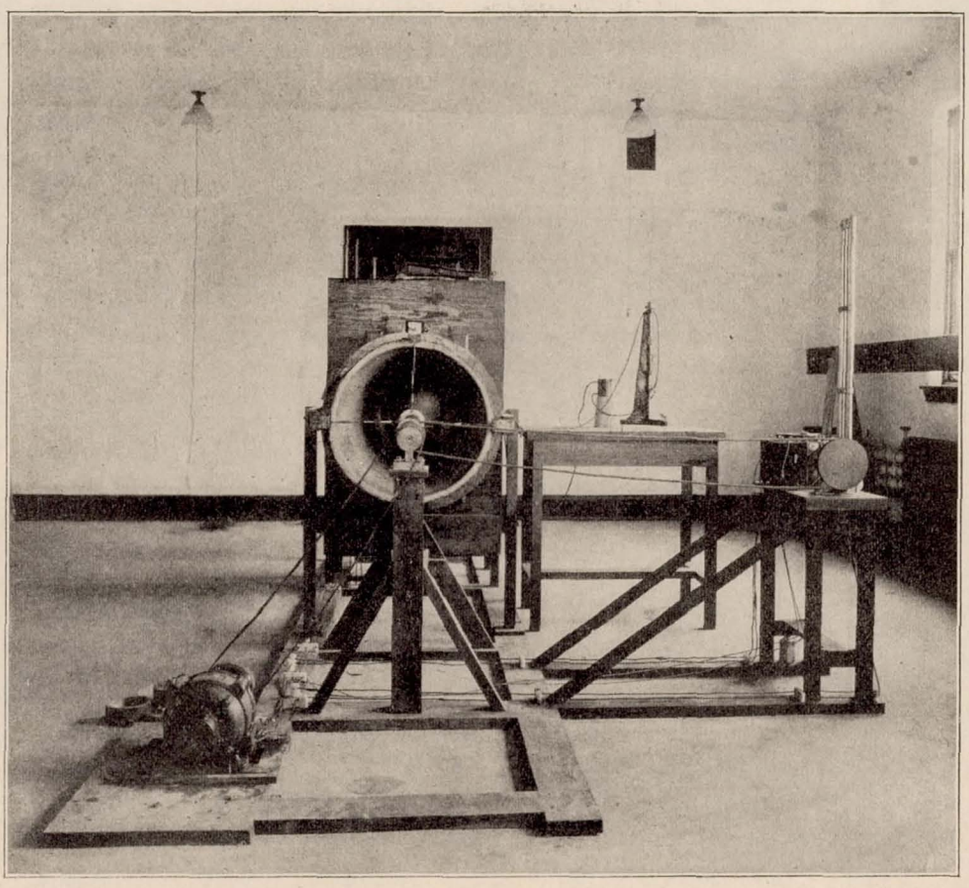


FIG. 8.

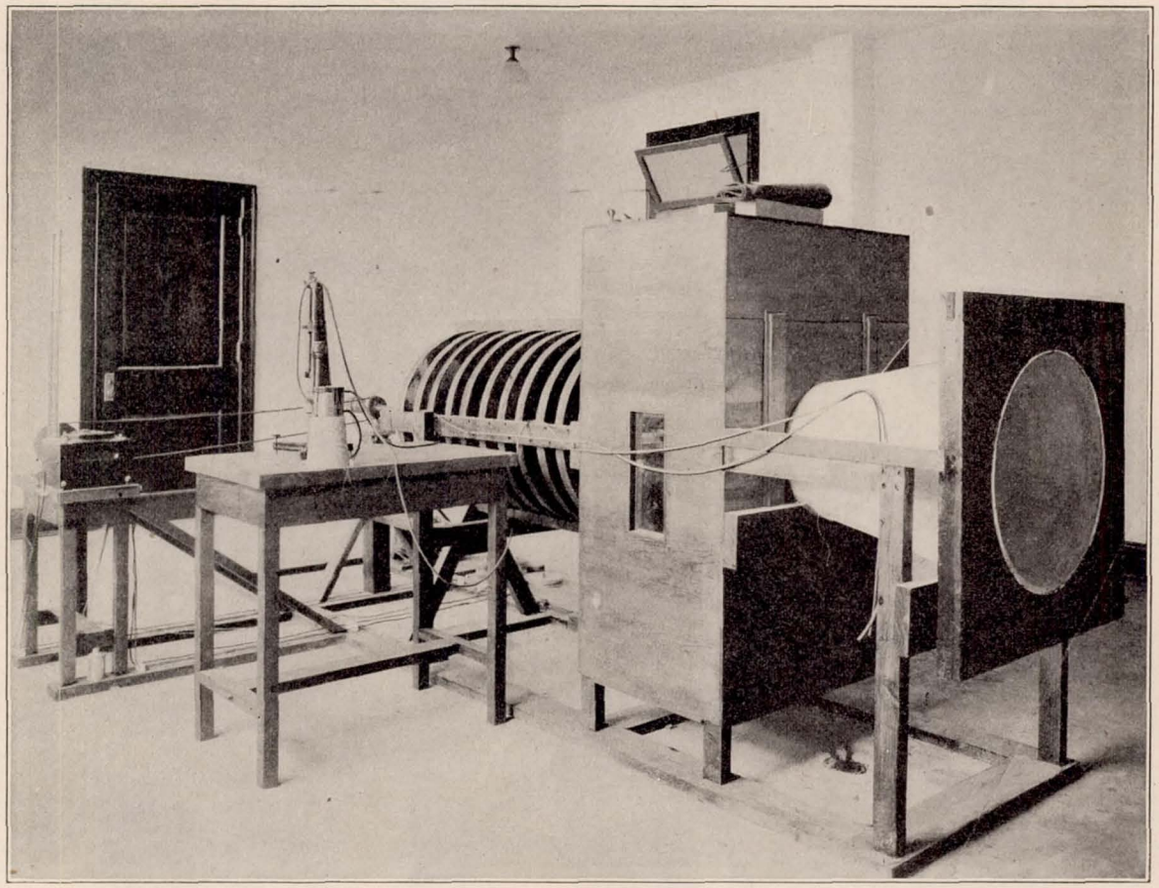


FIG. 9.

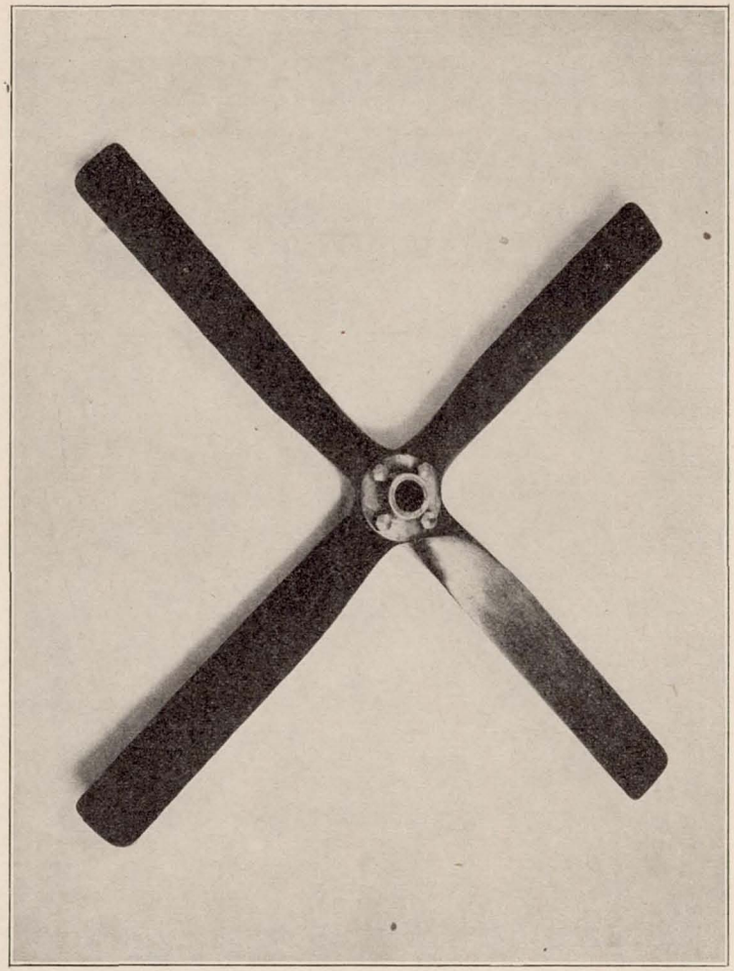


FIG. 10.

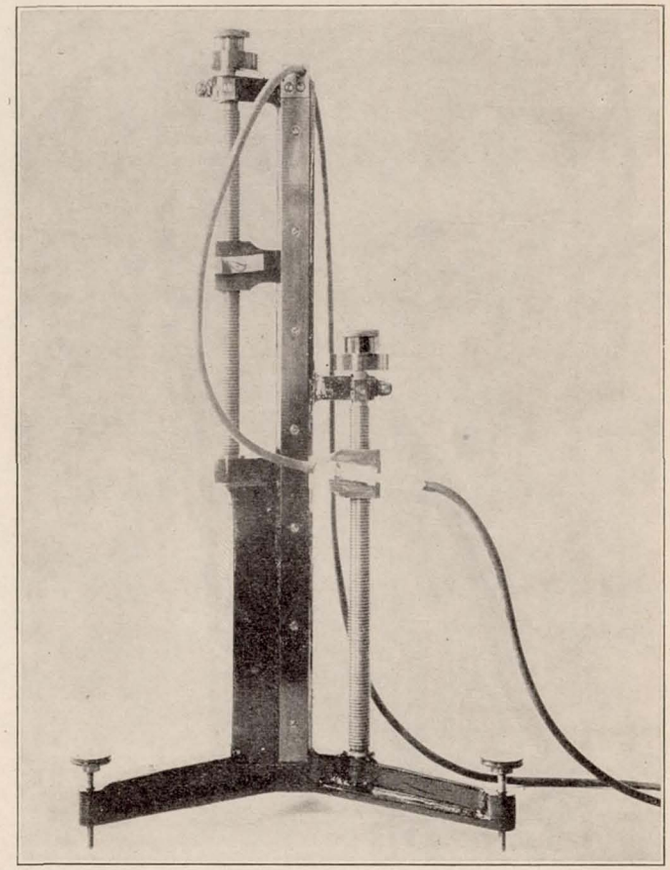


FIG. 12.—MANOMETER FOR MEASURING AIR SPEED IN WIND TUNNEL.

of the wall. On going still farther out the speed dropped rapidly, due to friction. The velocity in the experimental chamber near the entrance cone was constant, as nearly as could be detected, over 90 per cent of the diameter of the stream. On going farther downstream the velocity

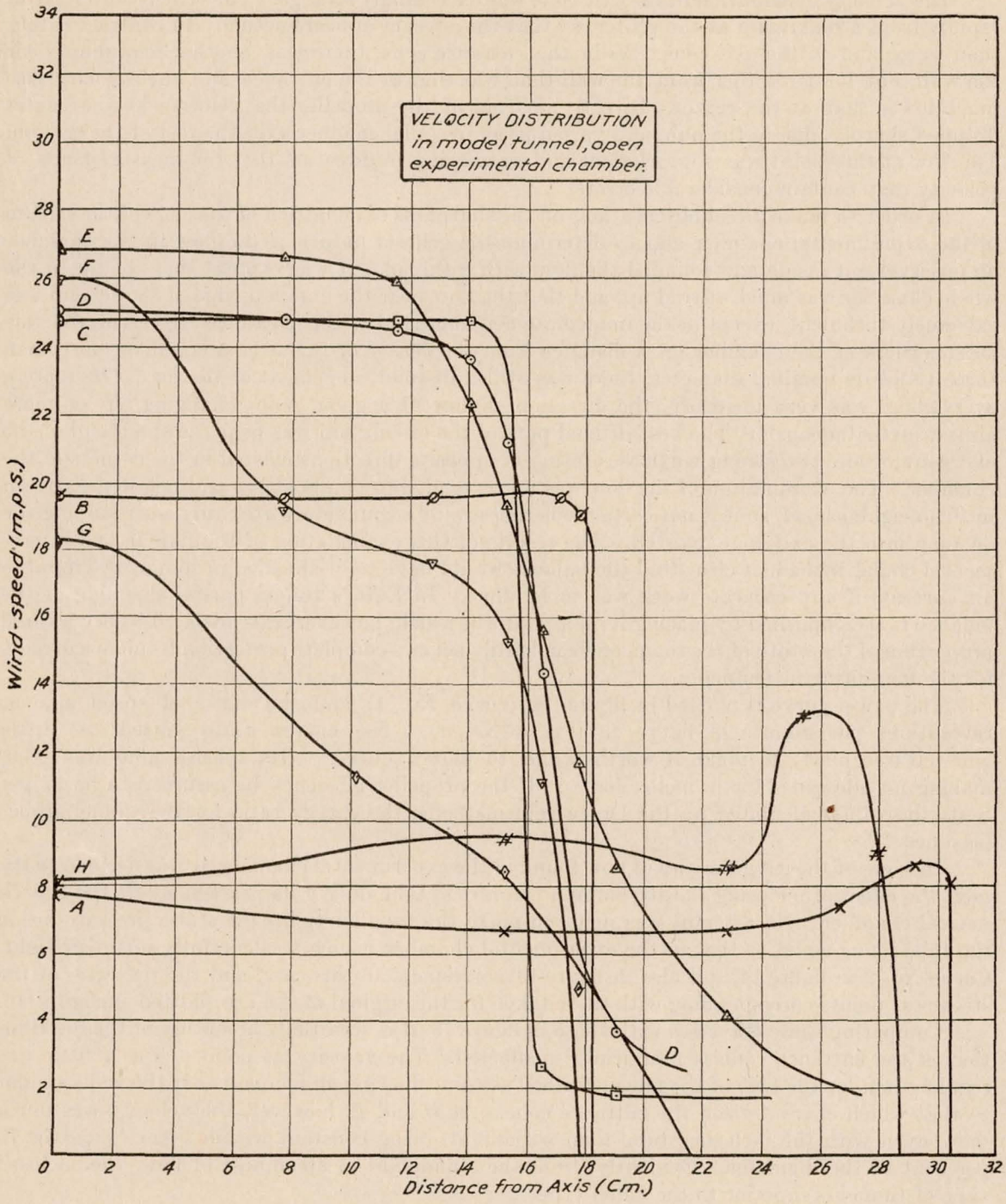


FIG. 13.

distribution became more irregular, the speed being a maximum at the center and dropping off steadily toward the edges of the stream. The ratio of the velocity 75 per cent of the way out to the edge of the stream to that at the center was 1.00 at *C*, 0.97 at *D*, and 0.96 at *E*. The edge of the stream was not sharply defined, even very near to the point of issuance from the

entrance cone, and at *E*, three-quarters of the way across the chamber, the velocity dropped off in a smooth curve from very near the center of the stream out to far beyond its normal boundaries.

The velocity distribution in the exit cone was exceedingly strange. The velocity dropped off rapidly from a maximum at the center, so that the stream appears actually to contract rather than to expand in the exit cone. As in the entrance cone, there was another maximum near the wall, but it was farther from the wall than was that at the entrance, and the velocity was much lower than at the center. Directly in front of the propeller the velocity at the center dropped sharply, due to the hub, and varied in an irregular manner over the rest of the section. The flow at this point was so turbulent and so varying in direction that the measurements of velocity may contain considerable errors.

In order to make direct observations on the sharpness of definition of the edge of the stream in the experimental chamber and to determine the general nature of the flow in the chamber an observer got inside and sounded the flow with a thread. It was evident that the air in the whole chamber was much stirred up, and that the flow near the nominal edge of the stream was extremely turbulent, except in the immediate neighborhood of the entrance. Even in the farthest corners of the chamber, at a distance from the center of the stream equal to more than three times its nominal diameter, there was still a distinct movement of the air. The motion everywhere was very unsteady, the direction of flow at a given point changing 60° or more almost instantaneously. The best defined part of the circulation was near the small end of the exit cone, where two strong vortices rotating in opposite directions existed in the corners of the chamber. The examination of the flow was not extended to points above and below the stream in this neighborhood, so it is not certain whether or not a complete vortex ring, surrounding the opening into the exit cone, existed. The results of this examination of the flow in the experimental chamber made it clear that the balance would have to be shielded in some way from the air currents if any accurate work was to be done. In Eiffel's tunnel partial shielding of the balance is accomplished by placing it on a platform which, however, extends across only a small proportion of the width of the room, and can hardly act as a complete protection from air-currents for the measuring instruments.

The power curve is plotted in figure 14 (curve No. 1) and the curve of speed against revolutions per minute in figure 15 (curve No. 1). The energy ratio varied too little and too irregularly to make it worth while to plot a curve. Its mean value was 0.90, making no allowance for propeller losses. If the propeller efficiency be assumed to be 57 per cent (the value calculated by the Drzewiecki method), the energy ratio for the tunnel proper becomes 1.58.

In view of the irregularities of flow found in the experimental chamber it was decided to try next the effect of inclosing the stream in a cylindrical tube during its passage across the experimental chamber. No attempt was made to make the tube air-tight, the static pressure inside the tube being equal to that in the experimental chamber, which was carefully made air-tight. Curve No. 2 in figure 14, and also in figure 15, correspond to this case, and the traverses of the stream at points corresponding with those taken for the original model are plotted in figure 16.

Comparing these traverses with those in figure 13 it is seen that the nature of the distribution in the entrance cone is practically unaffected. The velocity at point *C* was a little less regular than for the case of the unconstrained stream, showing an increase near the walls similar to that which characterized the entrance cone. At *D* and *E*, however, the velocity was much more even with the inclosing tube than without it, being constant within 1 per cent over 75 per cent of the diameter. Evidently, from the standpoint of steadiness of flow, the inclosed type of tunnel is superior to the Eiffel type.

In the exit cone the effect of surrounding the stream with a definite boundary was still more apparent. At *F* the velocity three-quarters of the way from the center to the walls was 94 per cent of that at the center, as against 67 per cent in the original model. At *G* the corresponding figures were 82 per cent and 40 per cent. At *H* there was, as in the first case, a minimum at the center and two maxima, the distribution of velocity being reasonably uniform across the outer 70 per cent of the blade, which is the most effective portion.

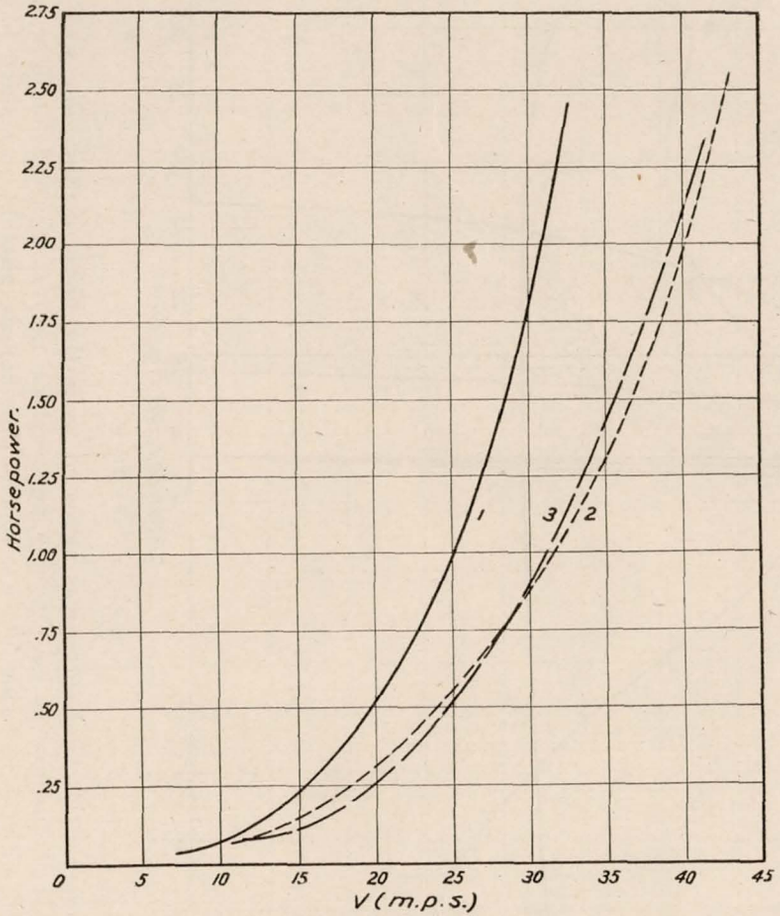

Horsepower.
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
.75
.50
.25
0
5
10
15
20
25
30
35
40
45
V (m.p.s.)
1
3
2

FIG 14

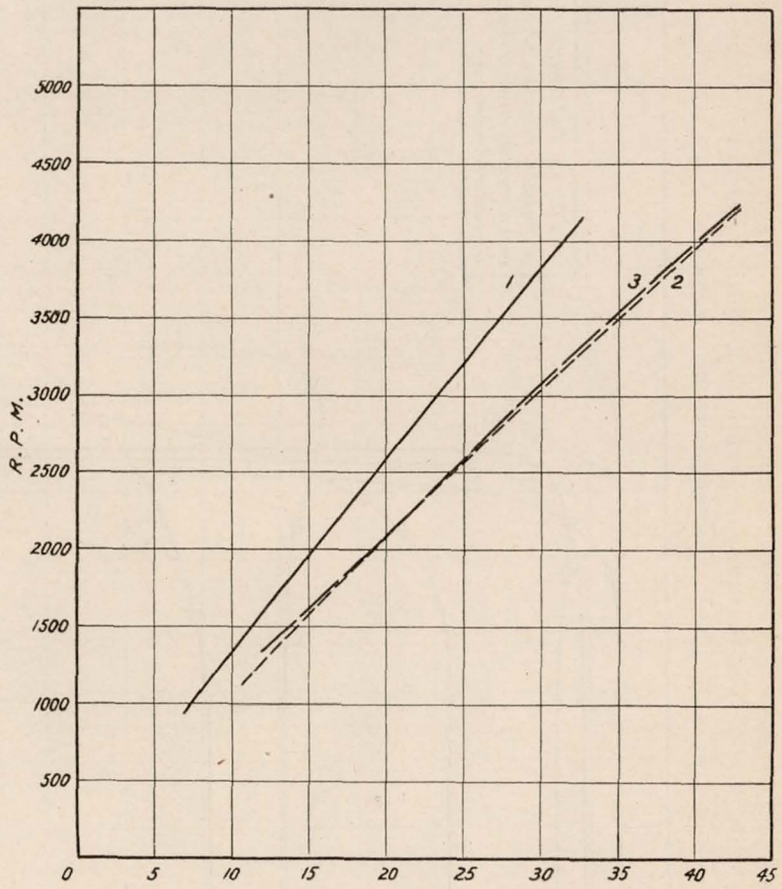

R. P. M.
5000
4500
4000
3500
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2000
1500
1000
500
0
5
10
15
20
25
30
35
40
45
1
3
2

FIG. 15

It is reasonable to suppose, in view of the better filling of the exit cone and of the generally improved velocity distribution, that the energy ratio would be increased by inclosing the stream, and this supposition was fully justified by the power measurements. For a given rate of rotation

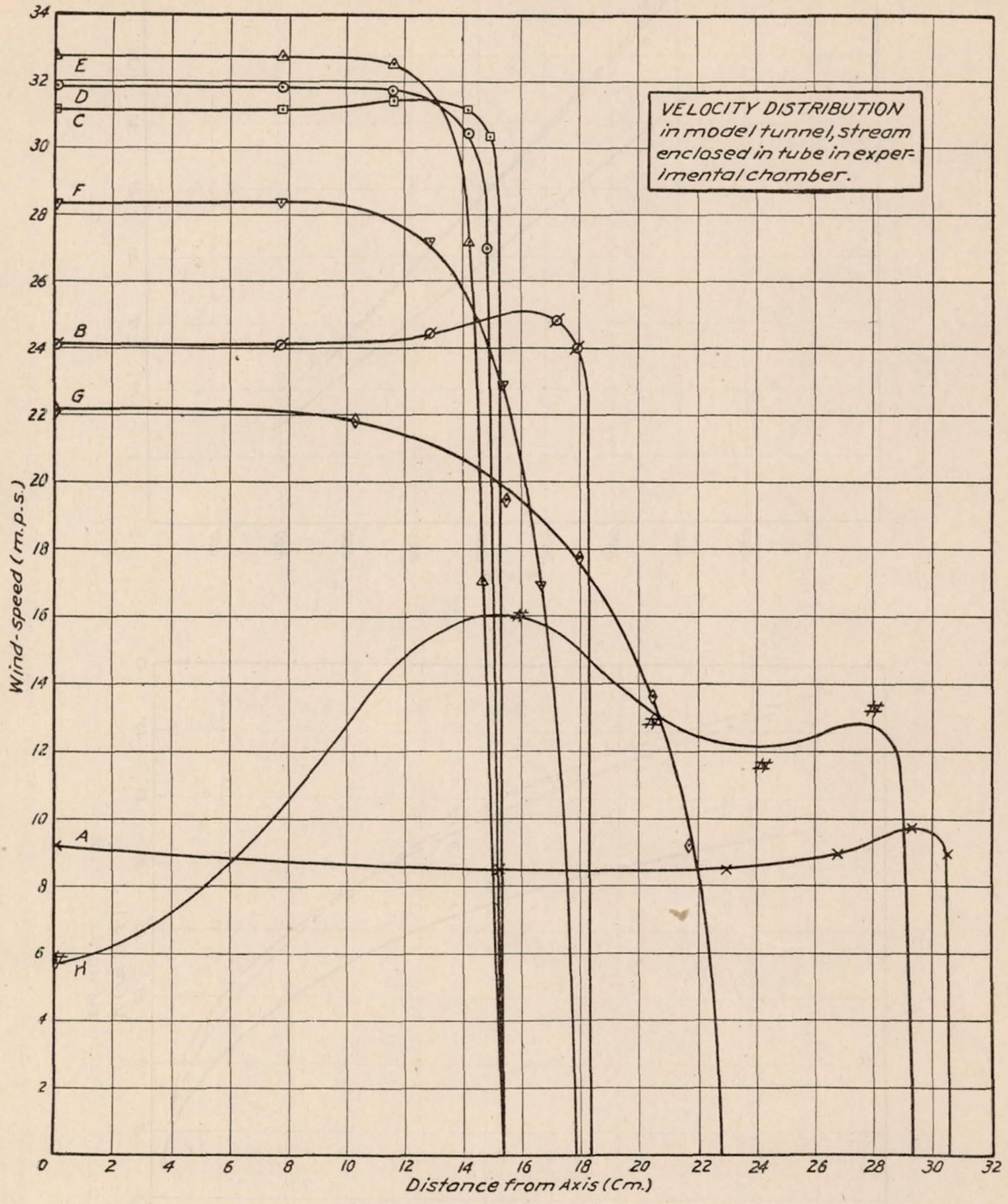


FIG. 16.

of the propeller the wind speed was increased while the power consumption was decreased, and the power consumption for a given wind speed was decreased just about 50 per cent. The energy ratio with the inclosing tube was 1.83 for the whole installation, or, making due allowance for the propeller losses, 3.20 for the tunnel alone.

It is evident that the inclosure of the stream improves the results in every way. The results obtained in these experiments, so far as power consumption is concerned, check very well with those obtained in some similar experiments on model tunnels, carried out by Lieut. Castellazzi.[1] Lieut. Castellazzi found that the efficiency was decreased 40 per cent by the use of an open experimental chamber. The experimental chamber used in his experiments was round in cross section and was twice as large in diameter as the entrance and exit cones where they entered the chamber, and the slightly greater loss in efficiency found in the experiments conducted at Langley Field may be accounted for by the larger size and more irregular form of the experimental chamber there employed.

EFFECTS OF VARIATION IN EXIT CONE FORM.

The next series of experiments dealt with the effect of alterations in exit cone form. It was originally the intention to make a number of cones of different forms, but this plan was abandoned after two had been tried, and the experiments cover only the parabolic and straight forms of cone. These are as widely different from each other in respect of their acceleration curves as are any two forms which would be likely to be used.

The curves of power and revolutions per minute with the straight cone are plotted as curve No. 3 in figures 14 and 15. The mean energy ratio is 1.83 for the combination of tunnel and propeller, or 3.20 for the tunnel alone, values identical with those for the parabolic cone. It is evident from the curves that the effect of changing the exit cone from a parabolic to a straight form was very slight. The parabolic form seems to have a slight advantage at high values of VD and to be inferior at low values, but the difference between the two curves is in no case in excess of the possible experimental error. In view of these results it appears that the efficiency of a tunnel is not affected appreciably by exit cone form or by the nature of the acceleration in the cone, but only by its length, mean angle, and total expansion ratio.

The large acceleration suddenly imposed on the air at the juncture between the parallel-sided portion of the tunnel and a straight exit cone might be expected to cause turbulence, so that the flow would be less regular than with a parabolic or other smoothly curving form. No experimental data are available on this point as yet, as the experiments were temporarily halted by an accident to the propeller before traverses and investigations of the flow had been carried out with the straight cone.

OBSERVATIONS OF THE NATURE OF THE FLOW THROUGH THE PROPELLER.

The most noticeable feature of the flow behind the propeller is the great rapidity with which the slip stream spreads. Instead of contracting, as in the case of an airplane propeller, where the direction of inflow is unrestricted, the stream expands immediately on passing clear of the cone, the air changing its direction so that there is a strong movement of the air, in a direction approximately at right angles to the axis of the tunnel, at a distance of 30 cm. back and 50 cm. out radially from the edge of the exit cone.

The flow in the throat and cones was very steady at all points except near the edges of the stream. The velocity head varied with a total amplitude of oscillation of about 2 per cent of the head and a period of from 20 to 40 seconds. On passing the propeller the pulsations of velocity became much more marked. The period of the pulsations close behind the propeller was about half a second, and the maximum velocity was estimated to be about 50 per cent greater than the minimum, although no means of measuring and making a continuous record of a rapidly varying velocity were available. On going farther away from the propeller along the lines of flow of the air the pulsations steadily increased in violence and the period lengthened until, at a distance of about 80 cm. to the rear of the propeller, the flow consisted of a violent gust about every second, the velocity in the intervals between these gusts being so low as to be hardly perceptible. These observations on the nature of the flow and its variations held in a general way for all the models tried, but the pulsations of velocity were much more marked for the case where the experimental chamber was left open than for that where it was inclosed in a tube.

[1] Rendiconti dell'Instituto Centrale Aeronautico, 1917.

EXPERIMENTS ON THE EFFECT OF DISKS AND SPINNERS ON THE PROPELLER.

In order to secure some idea of the effect of enlarging the hub of a propeller or of attaching a spinner, some experiments were made with disks of wall board attached in front of and behind the propeller, and also with a paper cone projecting from the propeller into the exit cone. The results of these tests do not fairly represent what might be secured with a good spinner and a propeller especially designed for it, as the propeller pitch should be increased when a spinner is incorporated or the hub is enlarged, but they will give some idea of the effect.

The effect of placing a disk in front of the central portion of the propeller, the rear not being covered and the blades not being housed in any way, was to decrease the wind speed and increase the power consumption. The inner parts of the blades acted as a centrifugal blower, taking air in from the rear and throwing it out radially. The increase in power, with a disk half the diameter of the propeller, was 9 per cent, the decrease of speed with the same disk 19 per cent. With a disk only one-fifth the diameter of the propeller the speed was decreased 5 per cent. These measurements were made at a speed of 10 meters per second and with the parabolic exit cone. The relative loss by the addition of a disk was greater with the straight cone and at high speeds, the addition of a disk four-tenths the diameter of the propeller causing an increase of 28 per cent in power and a decrease of 19 per cent in speed at a speed of 34 meters a second with the straight exit cone. The energy ratio was decreased 59 per cent. All subsequent tests were made with the straight cone, and the losses would probably be less with other forms.

The addition of another disk of equal size behind the propeller, so preventing any flow in from the rear and out toward the tips, improved the performance as compared with the single disk in front of the propeller, but remained inferior to the original case with no shielding at all. The power was increased only 6 per cent as compared with the original case without any disks, but the speed was decreased 16 per cent and the energy ratio fell off 44 per cent. When the rear disk alone was in place, so that any air thrown radially outward had to come from inside the exit cone, the power was increased 6 per cent, the velocity decreased 5 per cent, and the energy ratio decreased 19 per cent, using the model without disks as a standard in all cases. The disk behind the propeller therefore gave better results than did complete sheathing, either in the form of disks or faired by a cone in front.

The addition of a cone, having a diameter equal to two-fifths the diameter of the exit cone at its large end and an altitude of one and a quarter times its own diameter, in front of the propeller decreased the power about 2 per cent and increased the speed 7 per cent as compared with the values for the disks alone, but the energy ratio was still 30 per cent lower than for the original case. It seems strange at first that the entire blocking off of a considerable portion of the blades should increase the power consumption for a given number of revolutions per minute, but the phenomenon can be accounted for by the higher air speed past the propeller when the area of the exit cone is constricted by enlarging the hub. The theory of the effect of an enlarged hub or spinner has been discussed in another section of this report.

It appears that the addition of a spinner or the enlargement of the hub caused serious loss in every case where it was tried with the straight cone. The loss with a parabolic cone is much less, and it is likely that, with a propeller properly designed to allow for the increased velocity due to the blocking off of part of the area of the exit cone by the spinner, results as good as those in the original case could be obtained. It may even be that they could be materially improved on, but this does not seem very probable in view of the uniformly poor results shown in these experiments, where the presence of the spinner can hardly have decreased the propeller efficiency more than 10 per cent (a loss which, as already noted, could be prevented by the adoption of a propeller designed especially for the new conditions). The loss in propeller efficiency, therefore, would not be sufficient entirely to account for the decrease of energy ratio. The principal value of a very large hub is to increase the power coefficient of the propeller and make possible the reduction of the peripheral speed for a given wind speed.

REPORT No. 74

CONSTRUCTION OF MODELS FOR TESTS IN WIND TUNNELS

BY

F. H. NORTON

Aerodynamical Laboratory, National Advisory Committee for Aeronautics,
Langley Field, Va.

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REPORT No. 74.

THE CONSTRUCTION OF MODELS FOR TESTS IN WIND TUNNELS.

By F. H. Norton.

INTRODUCTION.

It is the general tendency of model makers, especially those who are used to working in wood, to underestimate the accuracy required in the construction of models for wind tunnel tests. In most pattern making an error of a hundredth of an inch is of no importance, but if this error occurs on an aerofoil, the model is valueless for testing purposes. The model maker, however, is not always to blame for the errors in the model, for these are often due to inaccuracies in laying out the drawing of the model to a small scale. Also models that are not of the proper size or weight are difficult or impossible to test. For these reasons a large amount of time and material has been wasted in constructing models, perhaps well finished, but unsuitable for wind tunnel experiments. It is the purpose, therefore, of this report to describe the methods, materials, and sizes that have been successfully used in this work.

TYPES OF MODELS.

The type of model most tested in wind tunnels is the single aerofoil of standard size, for the purpose of determining the aerodynamic properties of a certain section. Single wings are also tested with varying aspect ratio and plan form, and biplane and triplane combinations are often tested without body or struts. The wings, whether tested alone or on a complete machine, require the most careful reproduction of any part of an airplane. If the aerofoil is thin it should be constructed of a light aluminum alloy, as thin wooden wings will not hold their shape, no matter how carefully made, and it is difficult to fasten a spindle into the end. Thick models like struts and propeller sections, however, are best constructed of wood. Metal aerofoils should be constructed to within 0.002 inch of the given ordinates, and wooden ones to 0.004 inch. The angle of incidence should not vary along the wing more than 0.1 of a degree, but a slight curvature along the span of the wing, giving an effect of dihedral or kathedral angle, does no harm. Unless a wing is intended for a special test, such as aspect ratio, it should always be of standard size to insure strict comparison between different sections. In 4-foot tunnels a section 3 by 18 inches is used, and in larger tunnels corresponding sizes. Whenever possible the wing should be held by an end spindle, threaded directly into the end of the wing if of metal, one-third of the distance from the leading edge. (Fig. 1.) All standard aerofoils should have square ends and an aspect ratio of 6.

Bodies, floats, and hulls are made of wood and need not be as accurately constructed as aerofoils. The maximum error, however, should be kept within 0.02 inch on large models and 0.01 inch on small ones. The spindle is usually attached to the body by screwing it into the wood, the spindle being made with a wood screw point. If the model is bulky it should be made of a light wood, hollowed out to reduce the weight, as every pound added to the model means an addition of about 3 pounds to the weight on the pivot point, for 2 pounds must be added to the lower part of the balance in order to keep the center of gravity stationary.

A complete model should have a span of about 18 inches (not more than 21 inches) for a 4-foot tunnel, and weigh not more than 3 pounds. It must not, however, be lightened in such a way as to cause deformations at high velocities. The wings should be correctly aligned in

incidence, stagger, sweepback, and dihedral within 0.1 of a degree. The stabilizer should be easily adjustable, and a line should be marked along the propeller axis on the side of the body, in order to facilitate lining the model in the tunnel. It has been usual to attach the spindle directly to the body of the airplane as shown in figure 2. This type of spindle, however, creates a large disturbance of the air flow that is hard to correct for, so that it seems better, whenever possible, to attach the spindle to the tip of the wing. (Fig. 3.) Models should have stream lined struts, but the wires are usually omitted, and unless the model is to be used for stability tests the control surfaces need not be movable.

Model propellers are so similar to the full-sized ones that little need be said in regard to their construction. They should have the same degree of accuracy as wooden aerofoils.

MATERIALS.

The materials used in constructing these models should be light and capable of holding their shape. Thin parts like struts and wings are best constructed of metal, but the other parts are usually made of wood. Wings can be made of pure aluminum, but this material is rather soft, and better results are obtained by using a harder alloy having better machining properties. Magnesium cuts easily and smoothly and is considerably lighter than aluminum, but at present is hard to cast without blowholes. Perhaps the best alloy for this purpose is the very common one with 8 per cent copper and 92 per cent aluminum. If it is desired to construct a wing of great permanence for a standard, or for tests at high speeds, it should be cut from steel, but this is at present a rather expensive process. An aerofoil for pressure distribution tests is best made of brass, because of the necessity of using solder. Wings of a more or less temporary character can be made of plaster or wax as described later.

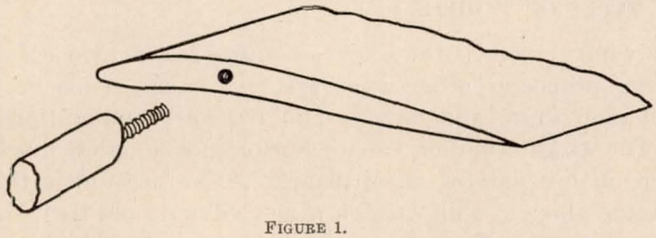


FIGURE 1.

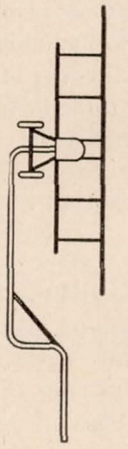


FIGURE 2.

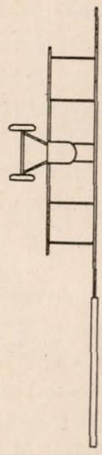


FIGURE 3.

Wood to be used for thick wings and bodies should be well seasoned and clear. As the expense for material is very small compared with labor expense, only the highest quality stock should be considered. The wood for aerofoils need not be light, but rather hard and close grained, such as maple, beech, boxwood, or holly. The maple is the easiest to procure and it is quite satisfactory when the stock is selected.

WOODEN AEROFOILS OF CONSTANT SECTION.

The process of making a 3 by 18 inch aerofoil will be described, the method, however, applying to any size of wing. This process has been successfully used for several years by Mr. Edward Tighe, model maker for the Massachusetts Institute of Technology. It should be remembered that, although wood can be worked to a very thin section, it will not hold its shape unless of considerable thickness, and the use of thin wooden aerofoils is not to be recommended where any permanency is desired.

A $\frac{7}{8}$-inch board of well-seasoned maple is cut along the grain into narrow strips that are planed $\frac{1}{4}$-inch wide. Every other strip is reversed and ten $\frac{1}{4}$-inch strips placed together with two face strips $\frac{1}{2}$-inch wide. This reversal of strips eliminates any tendency for the blank to curl, as each strip pulls in the opposite direction from its neighbors. The strips are placed in a drying oven and heated to about 100° C., spread with hot glue, and clamped together,

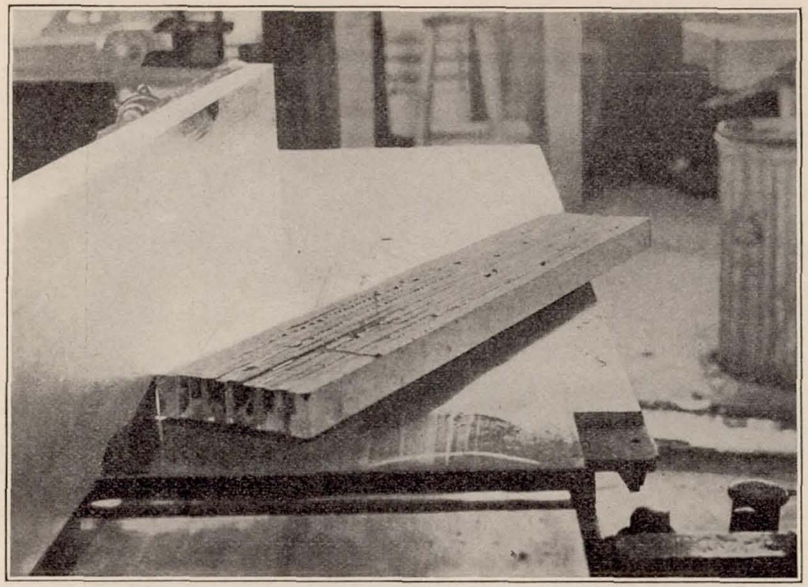


FIG. 4.

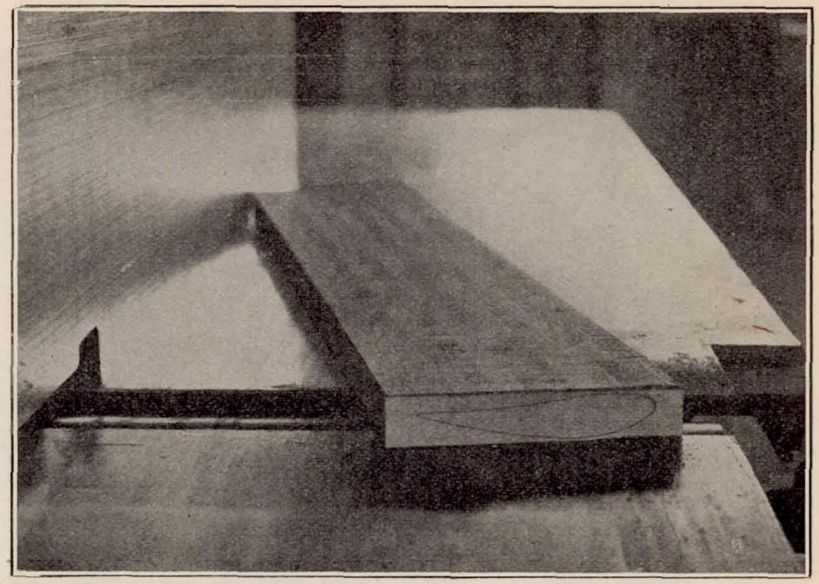


FIG. 5.

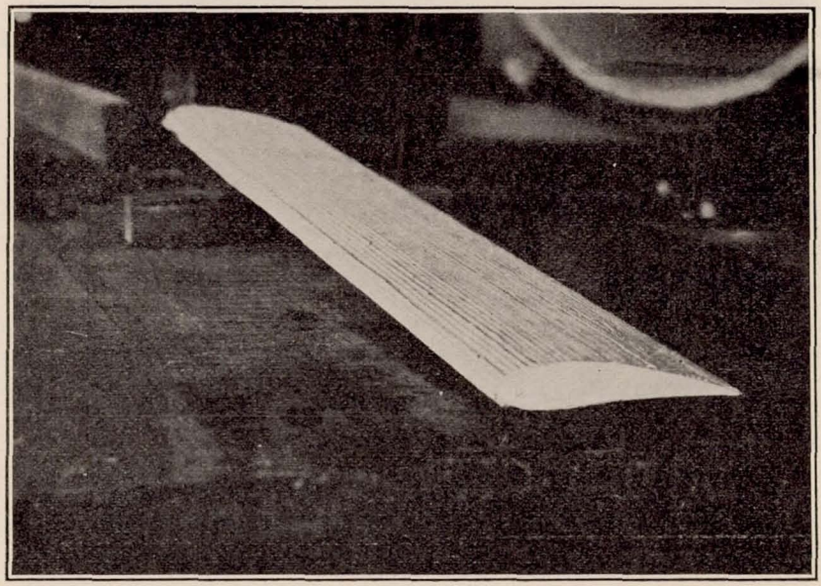


FIG. 6.

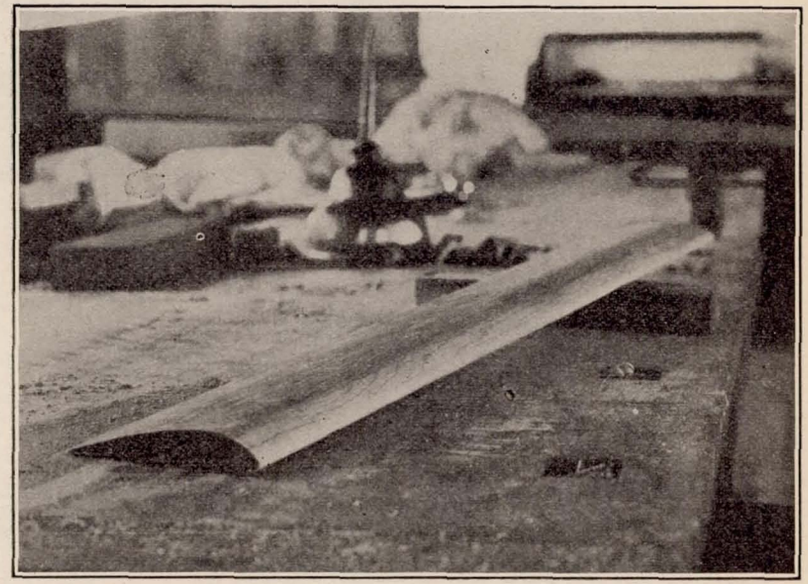


FIG. 8.

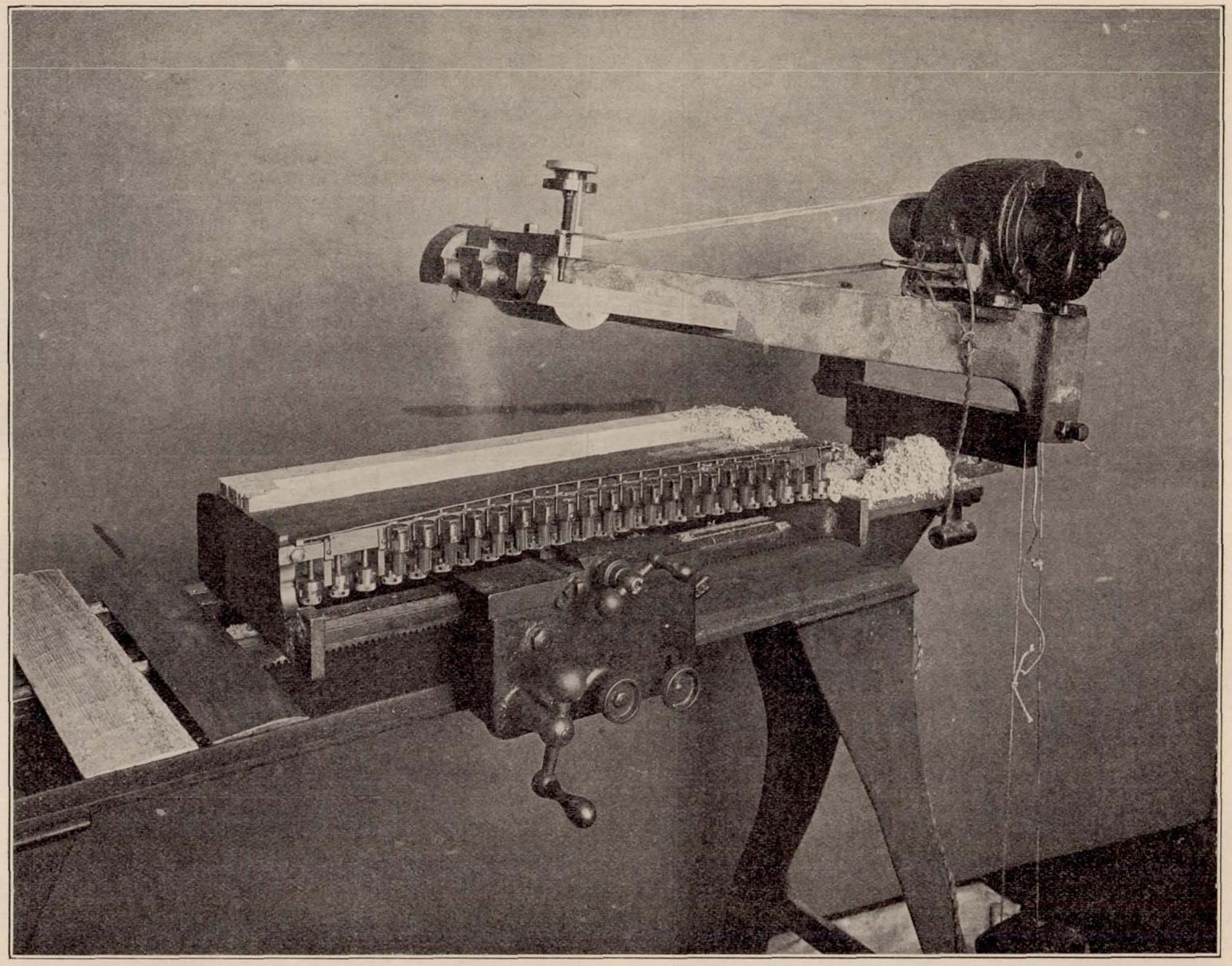


FIG. 9.

with heavy blocks on each side so that the total length will be under even pressure. The blank is left in the clamps for from 12 to 24 hours. It is then allowed to age for a few weeks to take up any initial warp (fig. 4). As the hardened glue, adhering to the faces of the blank quickly dulls edge tools, it should be removed as far as possible with a glue scraper.

Both faces of the blank are now made flat and parallel on a planer. It is of the utmost importance in this work to keep all tools sharp, and the importance of always removing the same amount of material from the opposite faces of a piece of stock should also be emphasized, for if this is neglected the material will always curl toward the face from which the larger amount of stock is removed. When both faces are true one edge is squared up on the planer and the ends are trimmed off on the circular saw, making the blank ready for cutting to the desired section.

An accurate outline of the desired section is drawn with India ink on white paper on a 15-inch or a 30-inch chord, using a medium fine line. This drawing is carefully stretched on a board and photographed on a process plate to a 3-inch chord. If this negative is printed on contrast paper a fine black line should result on a white background. The error in length of the reduced section should not be more than half a hundredth of an inch, which may require several trials in focusing. The print is trimmed and fastened to the end of the blank, preferably with vegetable glue. (Fig. 5.)

A saw table is set up with a sharp, rather wide, rip saw, hollow ground but having no set. The trued edge of the blank is placed against the saw guide and a light cut is taken along one face of the wing, and the depth is gradually increased until the saw just touches the black line on the photographed section. The guide is moved along about the width of the saw and the cut repeated, with a proper depth to touch the section at the new point. A magnifying glass is useful to accurately gauge the depth of the cut. After a few cuts have been made in this manner the blank is turned over and the same operation is repeated on the back, in order to prevent warping. This process is continued until all the wood has been removed except a few ridges to support the blank on the saw table. These ridges are now removed and the blank is ready for trimming. (Fig 6.)

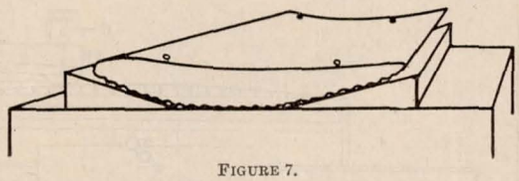


FIGURE 7.

The wing is held down to the bench by brads in the end and the irregular faces are wedged up in order to prevent strain as shown in figure 7. The terraces left by the saw are carefully planed down with a fine set plane until the grooves just disappear. A convex plane is required for concave surfaces, but should be sharp and set fine, as the maple may be somewhat cross-grained. The surface is next scraped with steel or glass to take out any lumps, is rubbed down with fine sandpaper, and the leading and trailing edges rounded off. After the ends of the wing are squared off to the proper length, the surface is filled, given two coats of shellac, and rubbed down with pumice. (Fig. 8.)

If this work is done carefully, the aerofoll wiil nowhere have an error of over 0.005 inch and the average error will be much smaller. It should be noted that any number of wings of the same section may be cut from one photographic section by running several blanks through the saw at each setting, care being taken to have the blanks of the same thickness.

WOODEN AEROFOILS OF VARYING SECTION.

Wings that do not have a constant section are much more difficult to construct than the usual type. They, may, of course, be worked down by template in the same way as a propeller blade, but as this is, at best, a rather long and inaccurate process, a special machine has been developed for this purpose. The principle of this machine consists in guiding a revolving cutter along a predetermined curve by means of an adjustable template. A general view of the machine is shown in figures 9 and 10. An iron bed plate (*a*) is mounted on the cross feed of an engine lathe, the overhanging ends steadied by guides (*K*) which rest on the ways, but allow the wing bed to be moved laterally and longitudinally in the same way as the tool

post. The wing blank (1) is screwed to the surface of this bed. A brass bar (*b*) is fastened to the front of the bed plate, and carries 25 micrometer screws spaced 1 inch on centers. These screws are $\frac{1}{4}$-inch, 40 threads, with a spherical top and a 50-tooth gear pinned to the lower end.

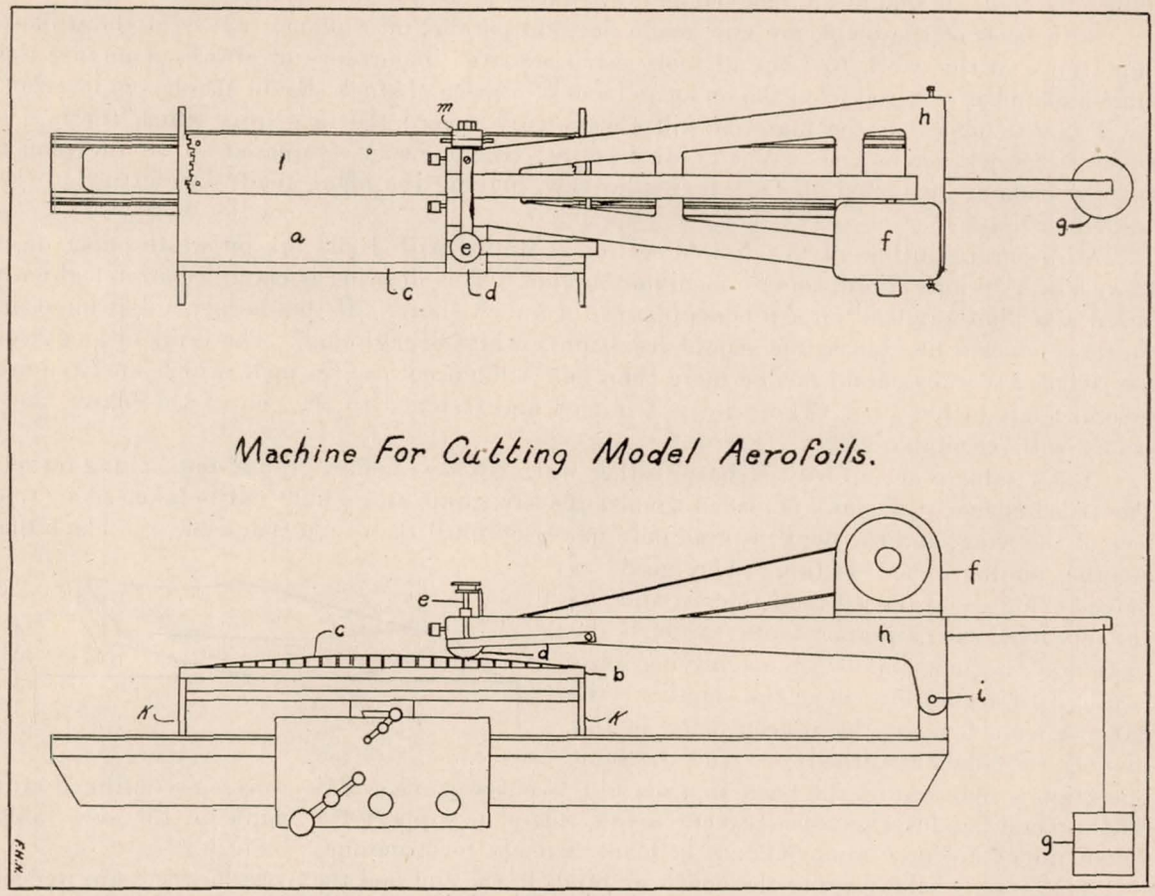
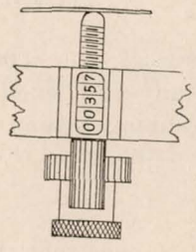


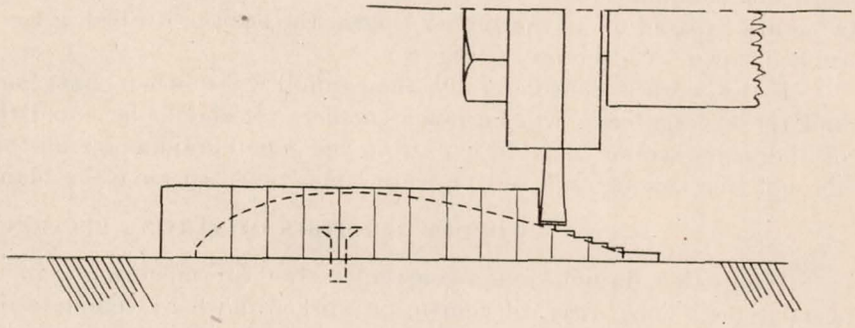
FIGURE 10.

In order to make the setting of so many screws quick and accurate, a direct reading counter was geared directly to each one as shown in figure 11. This device saved much time and many



Micrometer Details.

FIGURE 11.



Operation of Cutter

FIGURE 12.

mistakes, for 410 settings are required for each surface of a wing. A steel spring (*c*) rests on the rounded tops of the screws, forming a smooth adjustable guide for the shoe (*d*), which has the same radius of curvature as the cutter radius (3-inch). A spring $\frac{3}{4}$-inch wide and

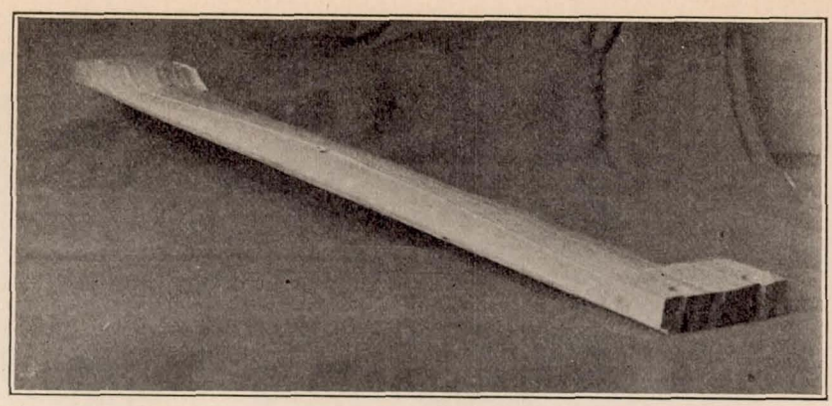


FIG. 13.

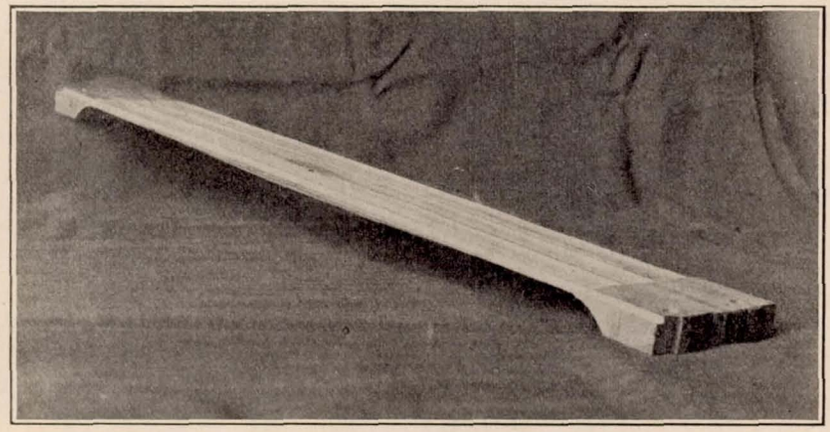


FIG. 14.

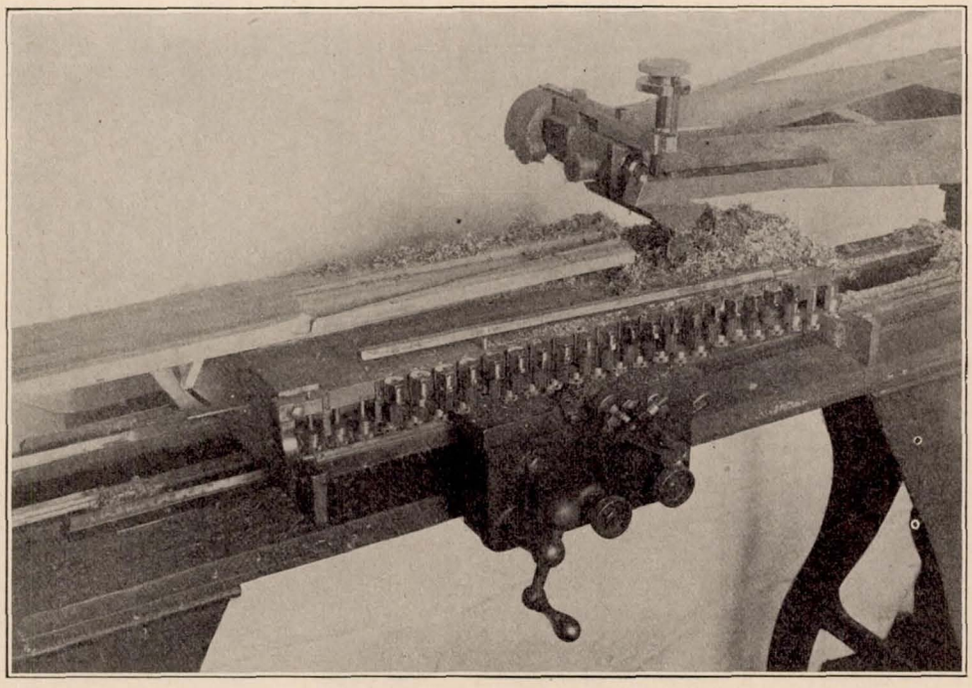


FIG. 15

0.038-inch thick was found best suited for ordinary work. A frame (*h*), pivoted at (*i*), and holding the $\frac{1}{6}$-horsepower motor (*f*) allows the cutter (*m*) to move only in a vertical direction. The cutter is made to follow the curve of the spring by the guide (*d*), which rests lightly on it. This is adjusted vertically by the screw (*e*) for cutting wings of uniform section (when the spring is horizontal) and for setting the cutter to the proper height after sharpening. For cutting wood a two-bladed cutter $\frac{1}{4}$-inch wide is driven at 5,000 revolutions per minute by a belt directly from the motor.

The material best suited for making models that are tested soon after completion, just as in the case of thick wings of uniform section, is laminated maple, and the blanks are made up in the way described for such wings in the preceding section of this report.

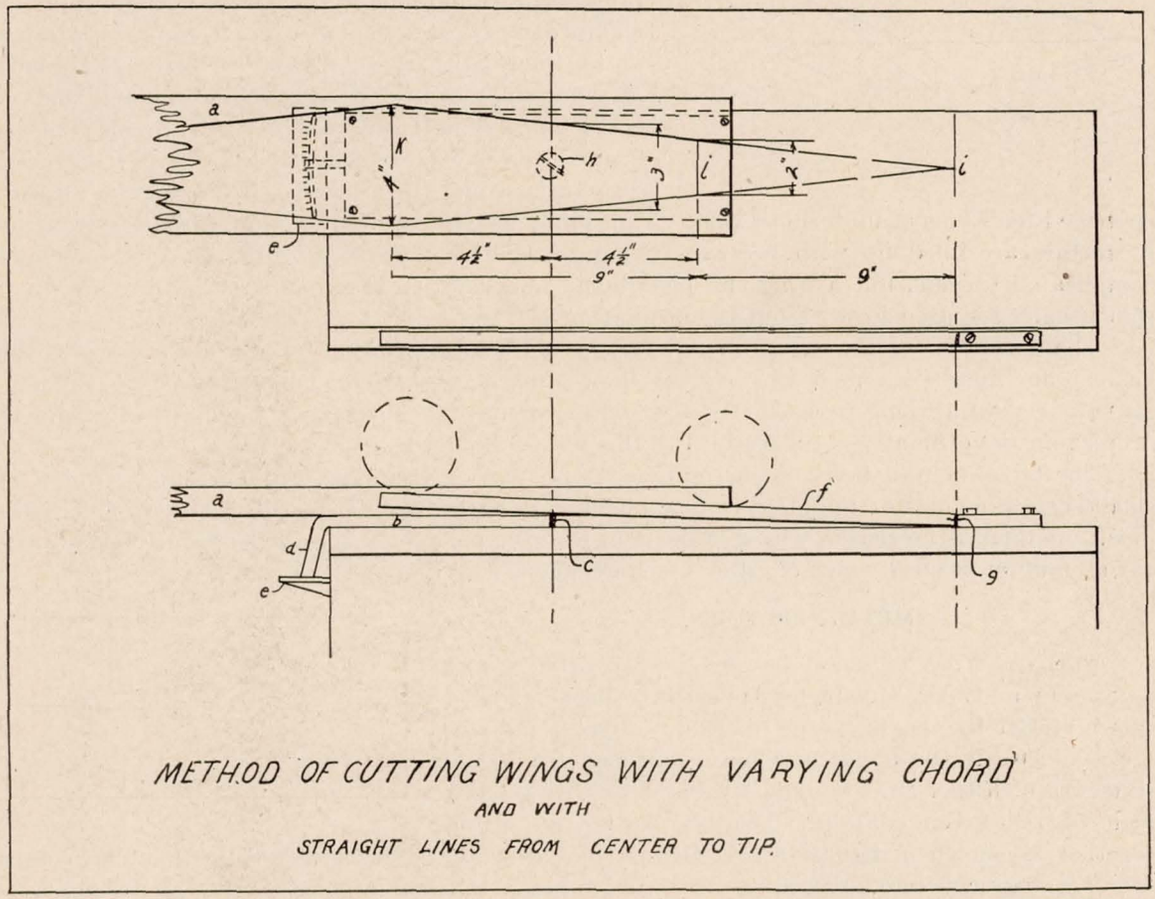


FIGURE 16.

The blank is screwed down to the base plate with 5 machine screws and the back is cut by starting $\frac{1}{4}$ inch from the leading edge of the blank and taking a cut across with the micrometer screws set for the first row of ordinates. The wing is moved laterally to the next position, and another cut taken. (Fig. 12.) This is repeated until the whole surface is cut. Three or four ridges should be left on the back of the wing in order to support it evenly when cutting the other face; also a groove should be cut for the spindle. The blank is then turned over and cut in the same manner on the other side. The surface is then an even set of terraces (photographs of the blank in this condition are shown in figs. 13 and 14).

A wing of constant section is made in the same way except that the steel spring is kept horizontally on the bedplate and the cutter is adjusted in height by the screw (*e*). This required only one-twentieth of the settings used by the varying section wings.

Figures 15 and 16 show an attachment for cutting wings with a varying chord and straight lines from an ordinate at the center section to a corresponding ordinate at the tip. The guide

rests on the straight bar (*c*), as only one-half of the wing can be cut at a time. The blank is screwed to the pivoted base plate (*b*) swinging about its axis (*h*). It will be noticed that the intersection of the leading and trailing edges prolonged (*i*) is opposite the hinge (*g*). With this arrangement it is only necessary to set the ordinates for the mean chord, as the others are automatically obtained from these by swinging the tip of the wing in the opposite direction from the movement of the cross slide when setting the cutter for the mean chord. The scale (*e*) is used to determine this distance. Wings having curved contours and tapering plan form can also be cut, but require a large amount of computation.

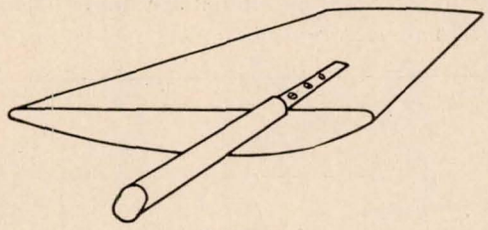


FIGURE 17.

When the section is completed on the machine, the ends are trimmed off, allowing a little extra length to prevent rounding off the corners. The wing is clamped down on a block of wood and the terraces are planed down as described before. The plane used for this purpose should be small enough not to cover up the part worked on. The plane can be ground concave or convex to fit irregular surfaces. The surfaces are then finished in the manner already described for wings of uniform section. The spindle is now screwed on, and any holes or errors in cutting are filled up with beeswax. (Fig. 17.) This may sound like a rather long and complicated process, but a wing can be cut and finished in 6 to 8 hours, a shorter time than that usually required to work out the ordinates.

The ordinates for these wings can be scaled off from a drawing on a 30-inch chord to the nearest one-hundredth inch which gives the ordinates for the model to a thousandth inch. As this is a rather long process, it is best wherever possible to make a single drawing and to proportion the ordinates of all sections to this with a slide rule.

The advantage of this machine is that it cuts a wing from the ordinates and requires no small scale drawings or templates. The machine described was designed to cut wooden aerofoils, but there is no reason why a stiffer and heavier machine could not be used to accurately cut aluminum or steel wings of either constant or varying section.

METAL AEROFOILS.

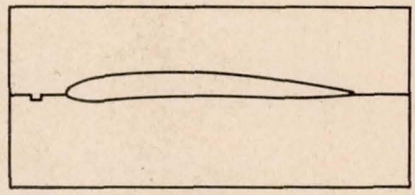


FIGURE 18.

The majority of aerofoils are best constructed of aluminum and very satisfactory ones have been made of this material by the following method. Steel templates are made to fit the upper and lower surfaces, from one-sixteenth inch tool steel worked by hand to within 0.001 inch of the given contour. The two halves are fitted together as shown in figure 18. It is well to check the dimensions of the templates on a dividing engine before proceeding further. A block of aluminum, preferably rolled stock, is trued up on one side to a plane surface. This surface is then clamped down to the bed of a small planer, and the upper surface is planed down to within about a hundredth of an inch of the finished size of the wing. The upper surface is now worked down by hand with file and scraper, using the plane surface as a reference, until it everywhere fits the template. This must be done very carefully by a skilled workman, and requires considerable time (from 30 to 100 hours). The lower surface is now worked down to fit the second template, using the upper template as a reference. In this way the wing is made straight and of uniform thickness. The ends of the wing are milled off square, and one end is drilled and tapped for spindle. This method should give a wing that is everywhere within 0.002 inch of the given dimensions.

Another method, applying mainly to brass and steel wings, makes use of a milling machine in the following manner: A slab of rolled brass or steel is trued up on one face and soldered to a trued heavy block that is fastened on the bed of a milling machine. The cutter is set

down until it just touches the lower block, and the edge of the wing blank is squared off. The cutter is now moved inward 0.05 inch and raised an amount determined by a table of ordinates for the section. These ordinates are scaled off of a drawing to 10 times scale in the same way as for the wooden sections. A series of cuts are taken across the wing until the upper surface is completely formed, leaving two narrow ridges to determine the original surface. The blank is unsoldered from the lower block, and the cut surface is filled with solder or lead and fastened down to the block, with the other face up, taking care that the ridges on the cut surface are in firm contact with the block. The squared edge of the blank is now lined up carefully with the milling machine ways, and the second surface is cut in the same manner as the first. After unsoldering the wing from the block all possible solder is wiped off, and the blank is ready for finishing. This is done by filing down the terraces until the grooves have just disappeared, which should leave a smooth and accurate surface. This method requires no templates nor as much skill as the preceding one, but is considered unsuitable for aluminum wings, as this metal does not hold solder, nor can it be machined to the finished size without the danger of tearing.

Brass wings can be cut with a one-toothed formed cutter, but it does not pay to make a cutter unless several wings of the same section are to be made. It is also rather difficult to get a smooth surface with this type of cutter.

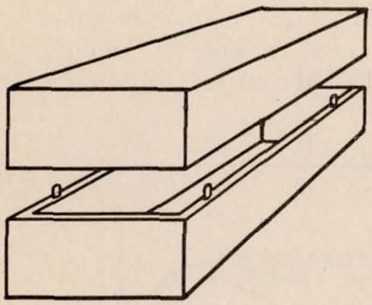


FIGURE 19.

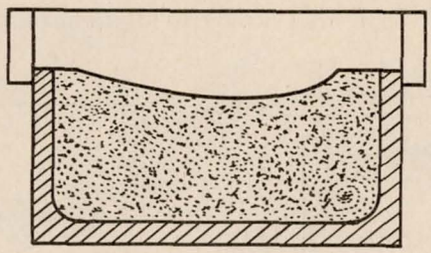


FIGURE 20.

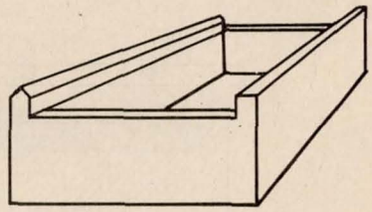


FIGURE 21.

As the wind speed in which aerofoils are tested is increased beyond 100 miles an hour it is necessary to use steel for models in order to prevent excessive deflection of the wing. Although it has apparently never been tried, it is probable that some method could be devised for machine grinding steel wings on a surface grinder to a high degree of accuracy.

OTHER METHODS OF MAKING AEROFOILS.

It is sometimes convenient to make aeroifols up in a quicker and less permanent manner, when they are to be used only for one test soon after construction. It is also desirable to be able easily to make a small change in some particular region of the wing without making a new model. The following methods have been used successfully here and abroad, but can probably be improved on by more extensive use.

The following method is used for making complete aerofoils. Two channel-shaped metal flasks, with upper edges machined are fitted together with dowel pins, as shown in figure 19. Two accurate templates (positive) are made to the sectional form of the wing, with lugs at the end to fit on the flask and guides to keep it square. (See fig. 20.) The flasks are now filled with well-calcined plaster of Paris that has been mixed into a rather thick paste. The templates are used as scrapers to roughly form the wet plaster to shape. After the plaster has set, the templates can be used to finish the molds down to the correct size. A very good finish can be obtained in this way, but the final finish should not be given until the plaster is dry or the shrinkage may distort the molds. The surfaces are now painted with linseed oil and the flask is clamped together. One end is plugged and a spindle held in the correct position. The spindle may well run completely through the wing as reenforcement. The mold may now be filled at the top with

a thin mixture of plaster or by some melted wax which possesses considerable hardness and strength when cool. After the mixture is set the wing is removed and the upper end trimmed off to the proper length. If carefully made the model should have a good finish and be, initially atl east, quite accurate. The wing will not be very permanent and should be tested soon after completion. Also it will not possess sufficient strength to make it available for tests at high speeds.

Another method of making plaster wings has been devised by the Curtiss Co. An iron bed having two trued ways (fig. 21) is nearly filled with a mixture of paraffin and Montan wax. When cold the wax is scraped down with a positive steel template to fit one surface of the wing. The template is carried on a carriage and can be gradually lowered as shown in figure 22. When this surface is completed a thin layer of wet plaster is spread on the wax and a sheet-steel core s pushed down to correspond with about the center of the wing, more plaster is added to the top, and is allowed to set. Before it becomes completely hard the template for the other surface is fastened in the carriage and the plaster is scraped down to size, the template being set to give the correct thickness. These wings can be made quite thin, but are not strong and must be handled with great care, and it is neccessary to support them with a center spindle.

When it is desired to make a series of changes in only one face of the aerofoil, it can be most conveniently done by taking a metal wing having the desired permanent surface, and with the other surface cut below any desired change on this part. Negative templates are made of thin sheet metal for all the desired forms, cut to slide over the leading and trailing edges, as shown in figure 23. The wing is placed in a shallow trough that fits the plan form of the wing and enough melted beeswax is poured over the desired surface to fill it above any desired contour. When the

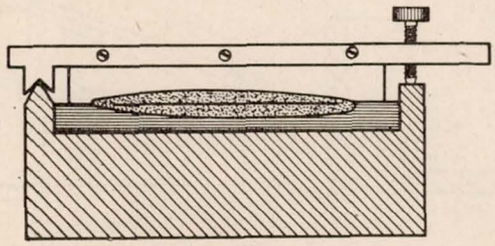


FIGURE 22.

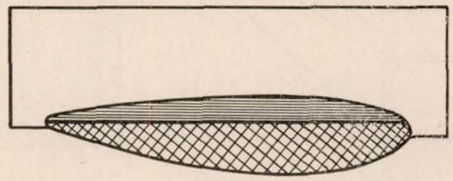


FIGURE 23.

wax has fully cooled it can be scraped down to the required size by template. The template may be held by hand, but a more satisfactory job can be done by holding it in a milling machine and running the model under it. In this way a very excellent surface can be formed equal in accuracy and finish to a wooden one. The wing must be tested within a few hours of the time it is scraped in order to be sure that the wax does not deform. The same method can be used with plasticine, but this material does not give as good results as the wax.

BODIES AND HULLS.

The construction of bodies and hulls requires less accuracy than wings, so that it will be necessary merely to outline the general methods used in their making. Large models should be cut to 0.02 inch and small ones to 0.01 inch of the given dimensions. For a 4-foot tunnel, no body should be more than 36 inches long nor 5 inches in diameter nor weigh more than 2 pounds, so that it is necessary to hollow all large models. The best woods to use for these models is white pine or bay mahogany, woods that are light, easy to work, and not liable to warp.

Small bodies may be made of one piece sawed out to the correct profile in two planes, as shown in figures 24 and 25. The edges cut off in the first sawing are lightly bradded on to the body in order to steady it when sawing the second side. The four sides are then planed down accurately to size, and by the aid of templates the corners are worked off with plane or spokeshave. The surface is then scraped and finished with shellac rubbed down with pumice and oil. If a fuselage has a spinner on the nose, it is best to turn this part down separately on a lathe and dowel it on to the fuselage, working the squared block down to the spinner. Cockpits should be cut to at least half the depth of the body, but no details inside, such as the seat, need be included.

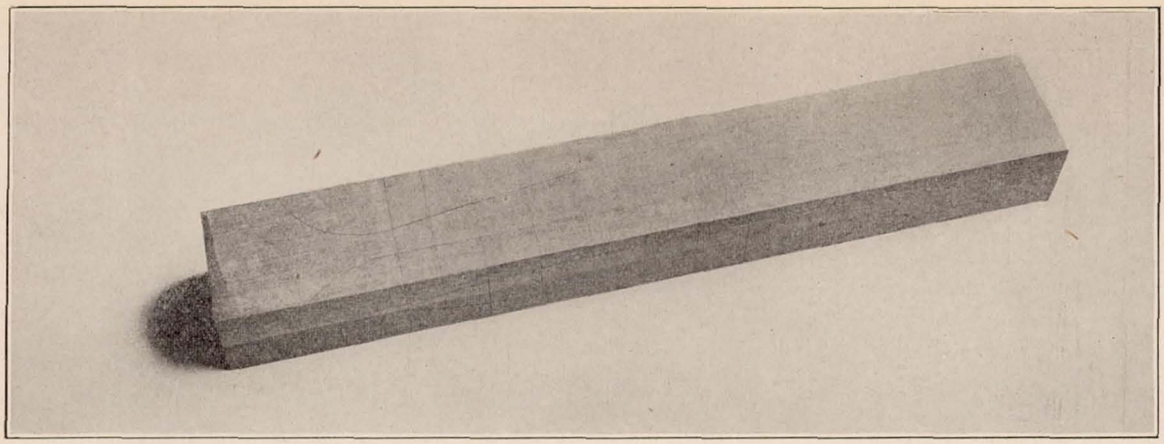


FIG. 24.

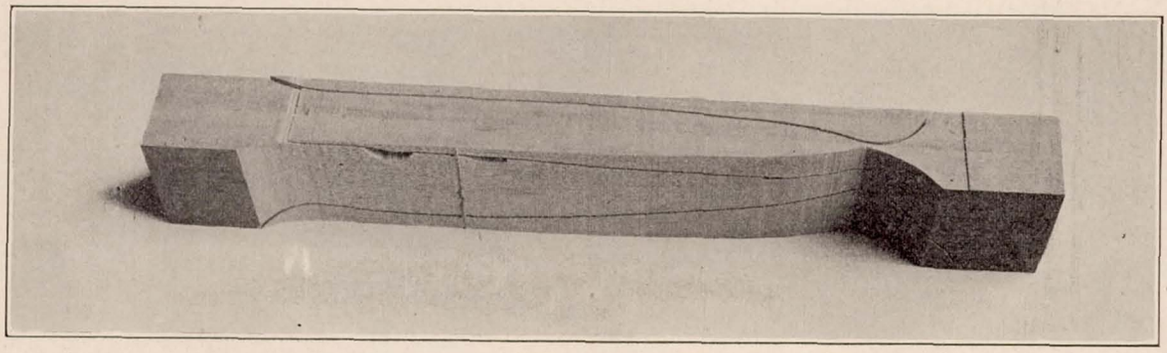


FIG. 25

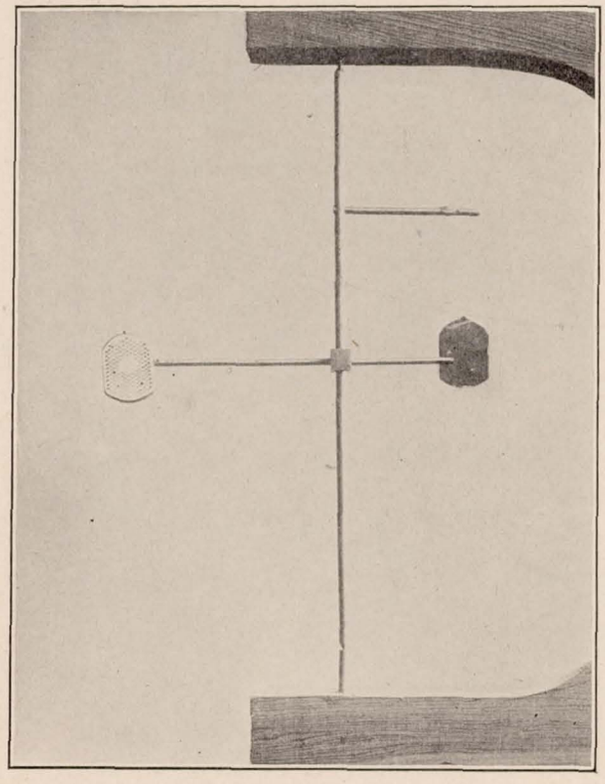


FIG. 34.

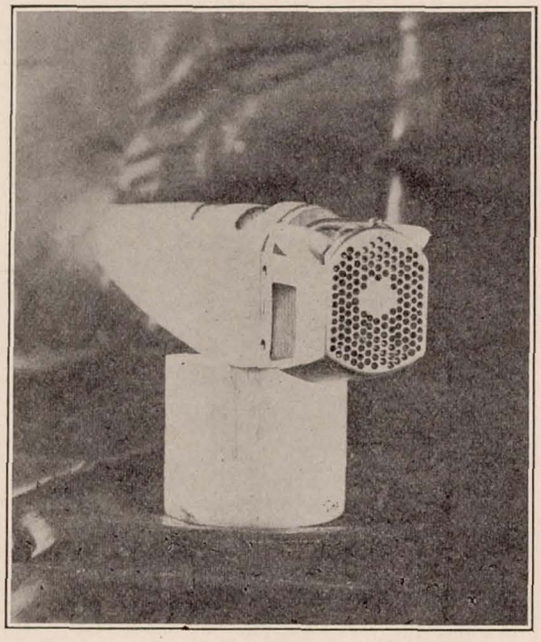


FIG. 35.

Wind shields, however, should be put in place and knobs representing the men's heads fastened to the rear of the cockpit.

Large bodies (over 18 inches long and 2½ inches in diameter) should be made hollow. This is best accomplished by cutting out a series of lifts from thin stock (¼ inch). These are sawed out and planed accurately to outline and the whole set glued together with hot glue, being held in alignment by dowel pins on the base plate as shown in figure 26. When the glue is hard the pins can be cut off flush and the outside surface of the model planed down smoothly to the contour lines of the lifts. This method gives a light and accurate model requiring few templates for finishing. A line should always be marked on the side of the body parallel with the propeller axis, in order to aid in lining up the model.

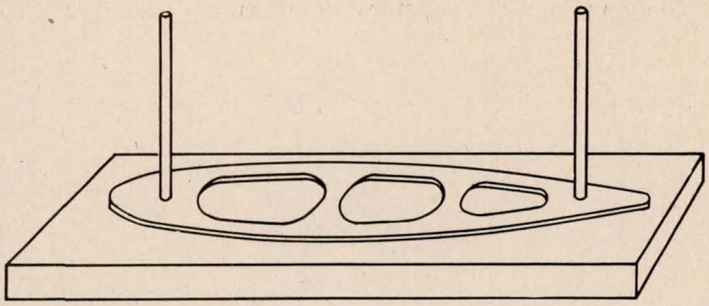


FIGURE 26.

Flying boat hulls and seaplane floats are constructed in the same way and require no special comment.

STABILIZERS.

Stabilizers can be worked out of aluminum in the same way as aerofoils and require the same degree of accuracy. If the stabilizer is thin it will not be too heavy if made of brass, which is preferable to aluminum in everything except weight.

It is important that the stablizer may be easily and accurately adjusted for angle of incidence. A maximum adjustment of 5 degrees is sufficient, but all mechanism for the adjustment must be in the body that it may not disturb the air flow. It is also desirable to have both halves of the stabilizer turn together.

A satisfactory and simple method is shown in figure 27. The two halves of the stabilizer are mortised out and fitted into the sides of the brass cylinder (*a*) with brass pins (*b*) all filed

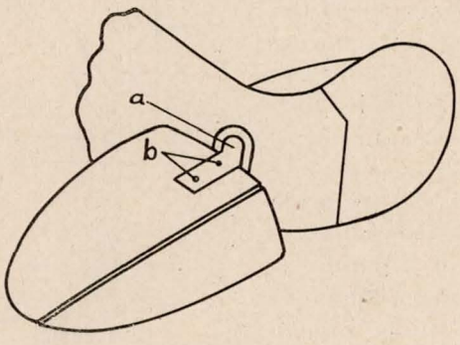


FIGURE 27.

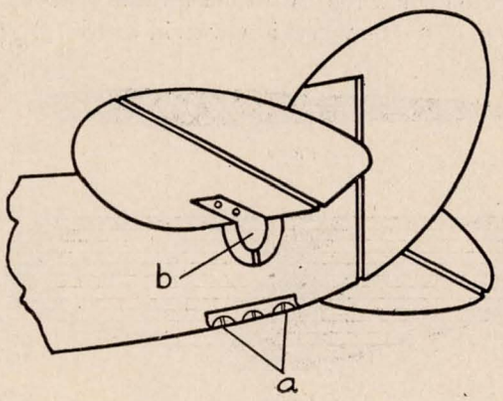


FIGURE 28.

flush with the stabilizer surface. The brass cylinder is a friction fit in the split ring (*c*) screwed into the wood of the body.

In figure 28 a similar arrangement is used except that a finer and more positive adjustment is assured by the two adjusting screws (*a*) passing from the bottom of the body to the sides of the brass cylinder (*b*). Figure 29 shows a way of adjusting a stabilizer that rests on the top longerons. A grooved brasss plate (*a*) is set in the top of the body, and a rocker on the lower side of the stabilizer rests on it. The angle is changed by adjusting screws at (*c*) and (*d*). Another method, figure 30, has the stabilizer hinged at (*a*) and the upper edge is held up against the screws (*b*) by springs. By adjusting these screws the angle is changed.

A template should be provided with every model to fit the stabilizer in order to line it up. The back of the template should be parallel to the stabilizer cord.

CONTROL SURFACES.

If it is desired to use the model for stability work, the ailerons, elevator, and rudder are made movable. The simplest and most satisfactory way to accomplish this is to cut the surfaces

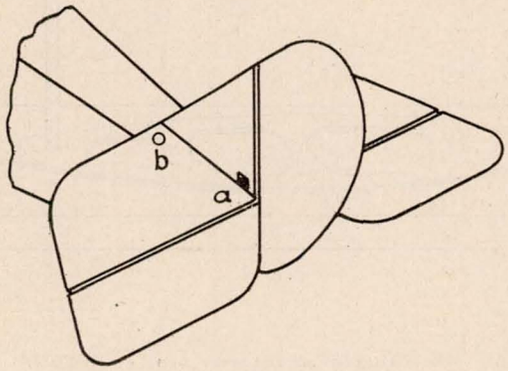


FIGURE 29.

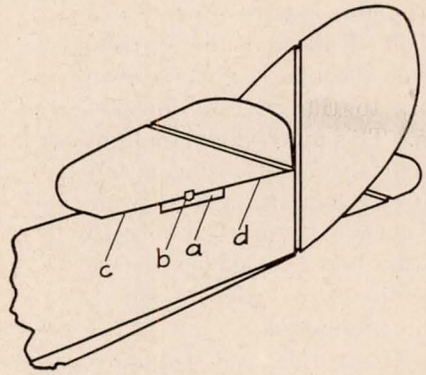


FIGURE 30.

with a very fine jeweler's saw, beveling the inside edges and inserting several pieces of soft brass wire as dowel pins. This allows the surface to be held in any position without danger of its turning. The size of the wires and their spacing depend, of course, on the size of the mode and the velocity at which it is tested. (Fig. 31.)

CHASSIS.

The wheels when small may be turned out of solid maple, but if the wheel is to be tested alone, and is therefore large, it should be glued up of pine laminations and left hollow. The laminations are sawed out roughly on the band saw, glued together, and then the whole is turned up and polished on a lathe. A cross section of such a wheel is shown in figure 32. The spindle is attached to the center of the wheel by screwing it into a brass socket, let in flush with the surface.

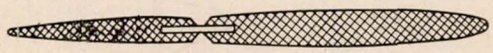


FIGURE 31.

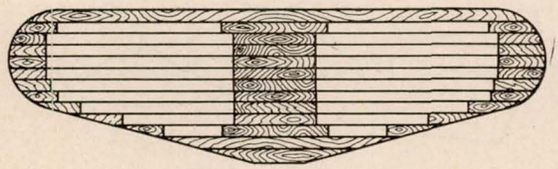


FIGURE 32.

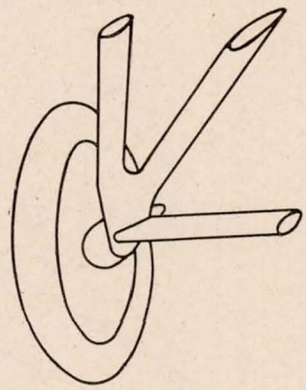


FIGURE 33.

Large struts should be made with the same degree of accuracy as wooden aerofoils and can be made in the same way. Small struts are made of metal, usually brass, in the following way, if great accuracy is desired. A rectangular strip of brass just large enough to contain the strut section is soldered to a heavy block of metal, and is lined up truly on the miller bed. A series of cuts are now taken along the strut with the corner of the cutter just touching the contour of the section, inscribed on the end, leaving a short uncut section at the other end in order to hold the strut square when this side is soldered to the block. The cut surface while still on the block is carefully filed down until the cutter marks have just disappeared, leaving the surface smooth and true. The strut is turned over and the operation repeated on the other side. If this is carefully done,

an accurate strut will result, but if greater precision is desired the cutter may be set by the micrometer head to a given set of ordinates, in the same way used in cutting aerofoils.

The axle is usually made like a strut and the wheels are pinned to the ends. Shock absorbers are fastened to the axle just inside the wheels with pins or glue, and are of stream-line form in most models. (Fig. 33.) Where the shock absorber on the full-sized machine is unstreamlined it may be reproduced on the model by winding a hard cord or wire of suitable size about the axle.

RADIATORS.

Although radiators are usually constructed of a solid block of wood, or are omitted altogether, there is no reason why this important portion of the structure should not be represented with fair exactness. This is accomplished by using a fine gauze screen, or, better, a perforated brass plate having the same resistance in proportion to a flat plate of the same size as has the full-sized radiator. In order to get the proper resistance the radiator and flat plate of the same size are mounted on opposite sides of a freely turning spindle, but at such a distance as gives a balance when the proper resistance of the radiator is reached. A short dummy spindle must be provided to counter balance the greater length of the spindle attached to the radiator. The holes in the radiator are gradually enlarged until it balances the plate. A model J N 4H radiator is shown in figure 34, mounted for balancing. The ratio of resistances between the radiator, and a flat plate of the same size ranges roughly from one-half to two-thirds, depending on the type of the radiator. A nose radiator should have a motor behind it and an outlet for the air in accordance with the large machine. A Hispano Suiza motor and radiator model is shown in figure 35.

THE COMPLETE MACHINE.

The completeness with which the minor parts of the airplane are reproduced on the model depends largely on the purpose for which it is tested. For instance, should the model be used only for determining the balance of the machine and the stabilizer setting, all small parts may be omitted, as they will not affect the balance appreciably. If, however, the model is used to determine the performance of the full-sized machine, or to obtain scale corrections, such parts as exhaust stacks, control arms, shock absorbers, etc., should be attached. To have strict agreement with the full-sized machine, wires and fittings, which furnish a large portion of the total drag, should be placed on the model, but, because of the difficulty of reproducing the wires and fittings on small models; and because the small wires do not have a resistence proportional to their size, wires have been omitted on practically all models. With a tractor-type radiator, the passage for the air to escape around the engine should be of the same proportions as in the full-sized machine. It would be very desirable to employ much larger models than are used now in order that all details might be included. With a 6-foot model it should be possible to very closely determine the performance of any new machine.

The wings of the model should be made of aluminum or steel by the methods described above, but usually with such a chord as to make the model some definite scale of the full-sized machine. The size of the model should be proportioned to the size of the tunnel, and the weight should be kept as low as possible consistent with stiffness at the maximum speed at which the model is to be run. Care should be taken on every part of the model to insure accuracy, finish, and sufficient strength to allow of handling.

When the wings are cut to the proper section, the plan form of the wing is laid out on the lower surface of each, with a fine scratched line. The outline is sawed roughly to size and then filed squarely to the line. By the aid of templates the ends are rounded off in the correct manner and carried smoothly into the finished surface of the wing. Wings having dihedral can be cut three-fourths through at the center section with a fine saw and the wing bent to the proper angle by means of templates. Sweep back, if present, is best accommodated by cutting the wing in the center to the proper angle on the milling machine and halving the pieces together, as shown in figure 36. The point of attachment of the struts is marked on the upper surface of each wing, and by means of tapered blocks the strut holes are bored and tapped.

(Fig. 37.) It is important that the direction of the holes be tapped exactly in the direction of the strut or it will be impossible to line the machine up closely. Also the threads in one wing should be right-handed and in the other left-handed. Another method of fastening interplane struts is to thread the ends of the struts and drill the wing, holding the struts to the wing with countersunk nuts, as shown in figure 38. This allows the use of stream-line struts, but they must be cut correctly to length as little adjustment can be made after assembly.

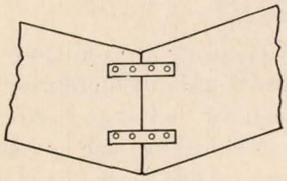


FIGURE 36.

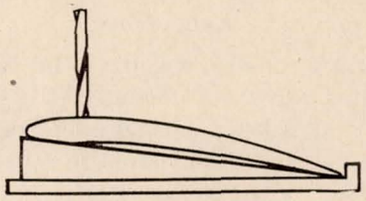


FIGURE 37.

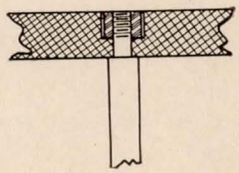


FIGURE 38.

Interplane struts having no incidence wires on the full-sized machine, as in the portal, I or K trusses, are made of a single piece of brass on the model and formed accurately to fit the surfaces of the wing. They are fastened with flat-headed screws passing through the wing, as shown in figure 39. This completes the work on the single wings.

The chassis is fastened to the body, either by pinning the struts into the body with pins that are continuations of the struts, or by bending the struts sharply as they meet the body so that the face of the strut is parallel with the side of the body and is mortised in flush with the surface and held by a small wood screw. If the lower wing passes through the body, as is generally the case, an accurate section of the wing is marked on the body, and with a fine band

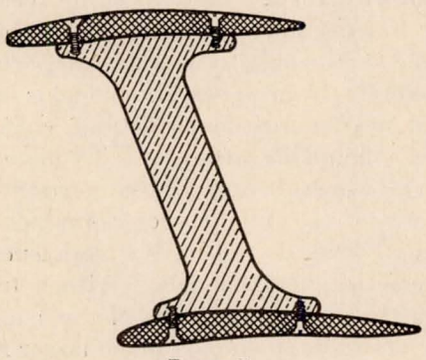


FIGURE 39.

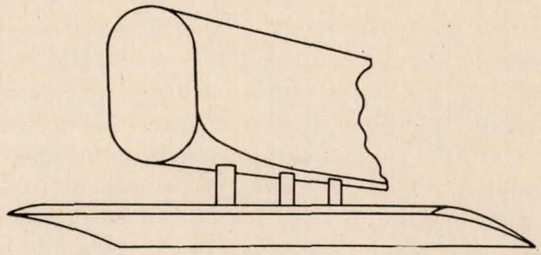


FIGURE 40.

saw the wood inside this section is cut away, with an entrance cut at the trailing edge. The lower wing can be slipped into this opening and screwed firmly in place by two wood screws inserted from below. Should the wing pass below the body, it can be held by long, slender wood screws passing through the wing into the body. The wing is held away from the body the correct distance by stream-lined spacers, as shown in figure 40.

The empennage is attached to the body, the leading edge of the stabilizer square with the axis of the body, and the fin and rudder parallel with the line of flight. The tail skid is usually made from the same piece of metal as the fin.

The body struts to the upper wing are attached in the same way as the chassis struts and are held at the other end by machine screws passing through the wing into the upper end of the strut. The interplane struts are made of a piece of steel wire cut to the right length and threaded on the ends with left and right threads. It is stream-lined when in place by a brass fairing.

The model is now ready for lining up, a process that must be done with the greatest care, in order that it may be relatively as well lined as the full-sized machine. In order to do this the fuselage is clamped securely to a plane surface, right side up and with the propeller axis

horizontal. A pair of similar templates are now made that will go under the chord of the upper and lower wings on either side of the body in such a way as to fix the angle of incidence of each, their stagger and dihedral. The position of these templates is shown in figure 41. The interplane struts are now put in place and approximately adjusted, and the lower plane is set to its correct angle of incidence by shimming where it passes through the body. With the aid of the templates the upper wing is adjusted by turning the struts, the opposite threads on which enable them to act as turnbuckles, until the wings are correct in all ways. The

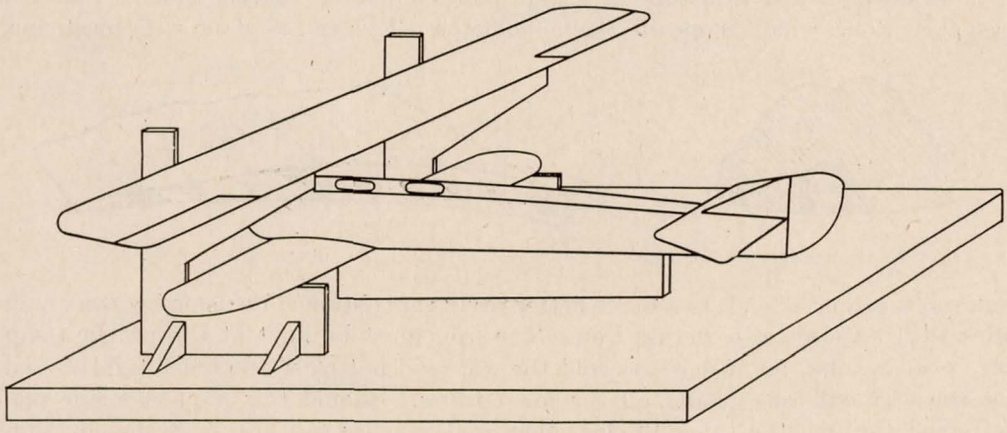


FIGURE 41.

brass fairings can now be attached with a soldering iron. They should all be lined up along the axis of the body. It is well to check up the alignment of the machine after mounting it on the balance in order to be sure that there is no error of more than one-tenth degree at any point.

The spindle is sometimes attached by screwing it directly into the wood of the body, but if the model is to be used several times a metal socket is best inserted in the wood, as shown in figure 42. This type of spindle, however, is rather unsatisfactory aerodynamically because of its interference with the wings and because it is difficult to determine its effective resistance; that is, the resistance which should be subtracted from the total resistance to give the true resistance of the machine. A better way is to screw the spindle into the tip of the wing. If the forces are large, it is necessary to insert a steel socket into aluminum wings. (Fig. 43.)

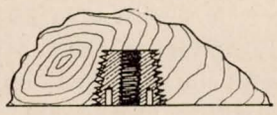


FIGURE 42.

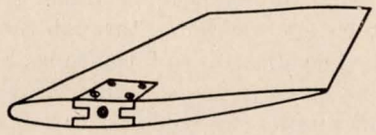


FIGURE 43.

AEROFOILS FOR PRESSURE DISTRIBUTION.

It is sometimes necessary to know the pressure on each portion of the surface of an aerofoil in order to determine the manner of loading. In order to do this a large number of small holes are bored into the wing at right angles to the surface and each in turn connected to a pressure gauge. As this requires a long time and the connections must not be allowed to interfere with the air flow, the following methods have been adopted:

A method devised by the National Physical Laboratory consists in cutting a series of grooves along each surface of a brass wing at right angles to the chord. They are about $\frac{1}{16}$ inch wide and deep, and are spaced closest together where the pressure gradient is steepest, but 10 or 12 rows is sufficient to each surface. A piece of $\frac{1}{16}$-inch steel hypodermic tube in each groove and smoothed off flush with the surface with solder. (Fig. 44.) A series of holes

are now bored along the tubes, on half the span only, as the wing is symmetrical. These holes should be spaced nearer together at the wing tip than at the center. They should be bored with a No. 70 drill and all burrs carefully removed. The tubes should project about $\frac{1}{4}$ inch beyond the wing tip on the side away from the holes in order to make connections with rubber tubes and yet not interfere with the air flow on the side where the pressure is being taken. (Fig. 45.) The other ends of the tubes are filed flush with the surface, but are left open, so that a cleaning wire may be pushed through the tube. The wing is placed in the tunnel, and each row of holes is connected to a tube of a multiple manometer. Every hole in each row must be closed except one, which is open to the manometer. This can be done with plasticine, but as

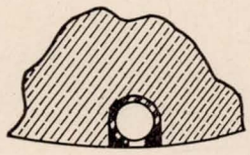


FIGURE 44.

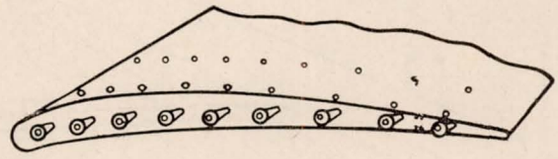


FIGURE 45.

this material is rather difficult to remove better results are obtained by using beeswax melted into the holes with an electric soldering iron. The iron must be kept at the proper temperature to insure good results, for if it is too cold the wax will not close the holes tightly, and if it is too hot the wax will run in and fill the main tubes. Should this happen a fine piano wire can be forced through the tubes to clear them. The holes can also be sealed by small disks of tissue covered with shellac. Care should be taken at each change of holes, to be sure that each hole that should be open is clear and that all the others are closed. This is easily determined by blowing against the wing at each hole with a small rubber tube and watching the manometer. There should be no deflection except at the open holes.

Another method devised in this country, although requiring a little more work on the model, has the advantage that it can be used on thinner sections, as ailerons and tail surfaces, and gives smoother surfaces. Two blocks of brass about $\frac{1}{4}$ inch thick and of sufficient size to construct the wing, are trued up on one face. These faces are then grooved at corresponding distances along the span under each row of holes. The grooves can be cut with any cutter that will give a square or circular hole when the two halves are placed together. The blocks are carefully tinned and are soldered face to face with $\frac{1}{16}$-inch aluminum wires in the grooves to prevent the solder filling them. The wires can be removed, leaving a series of clear air passages. Holes are now bored through the wing from face to face with a No. 70 drill, as shown in figure 46. The direction of the holes should be closely normal to the finished surface of the wing. The block can now be placed in the milling machine and worked down as described before. Small nipples are soldered to the end of the air passages on the opposite side of the wings from the holes for the attachment of rubber tubes, running clear of the model. Small tube should not be used any further than necessary, as it has a heavy damping effect on the gauge.

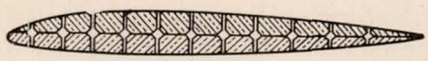


FIGURE 46.

When it is desired to investigate the pressure on a control surface the holes and passages are made in the same way, but it is now impossible to take off the pressure on the side of the machine opposite from that on which the pressure is measured. In order to reduce the interference to a minimum, fine steel hypodermic tubes are carried out several inches from the end of the wing before the rubber tube is attached, as shown in figure 47.

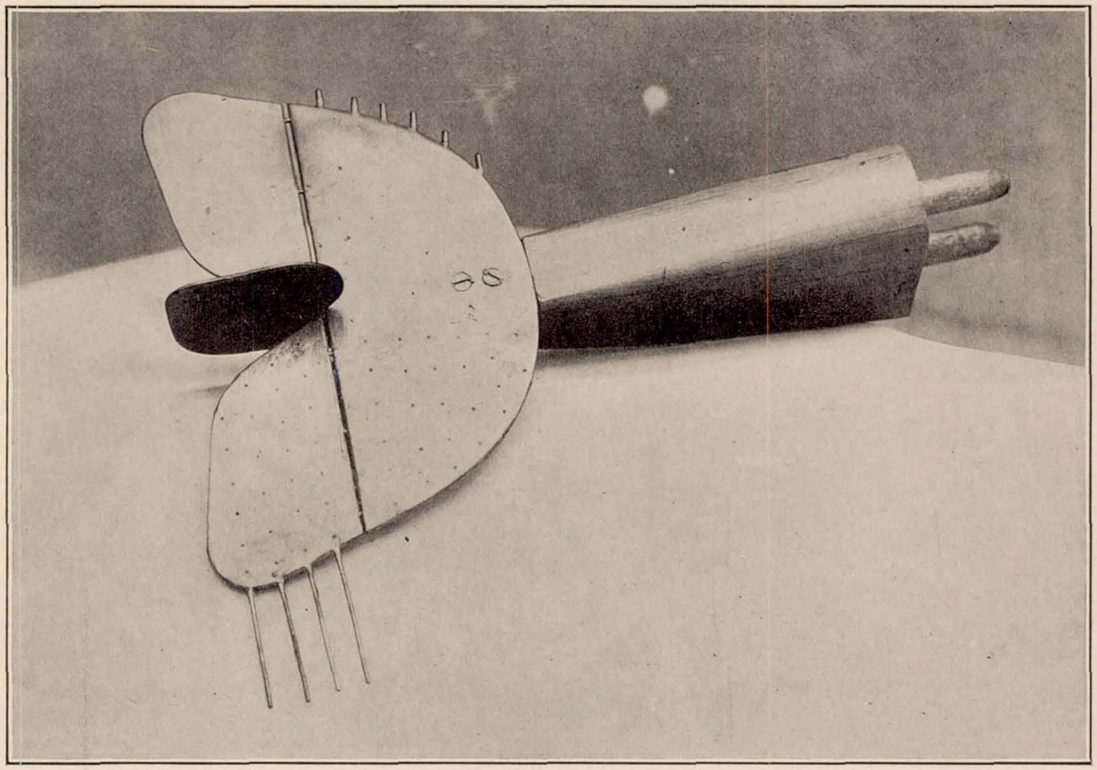


FIG. 47.

MODEL PROPELLERS.

Model propellers are so similar to full-sized ones that the same methods of construction apply to both. The method most generally employed consists in making a series of templates to fit both upper and lower surfaces of the blade at a series of stations along the radius. The position of these templates should be fixed by screwing them to a plate squarely and with their proper spacing. This allows all the templates to be applied to one face at a time. A series of laminations is glued to the proper thickness and cut out to the given contour. The blades are then worked down by hand to fit the templates, a rather slow and inaccurate method, but the best that has been used.

Another method consists in gluing up laminations that have first been cut to the exact size. The blades are then trimmed down to the contour lines, thus determining the blade. It is difficult to accurately cut the tip of the blade in this way, as the distance between aminations is large in this region.

All model propellers are laminated to prevent warping, the best woods being pine or mahogany, unless the blade has any thin sections, when a closer-grained wood like maple is better. A four-bladed propeller should have each pair of laminations halved together rather than to halve the whole propeller, in order to give a more uniform support to the blade. Each propeller should be carefully balanced and finished with shellac. A steel hub can be bolted to the propeller in the usual way. From the aerodynamic standpoint, it is desirable that the full-sized propeller and the model be made from the same material and by the same method, as the deformations of the blades of the two at like peripheral speeds should then be identical.

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REPORT No. 75

THE AERODYNAMIC PROPERTIES OF THICK AEROFOILS SUITABLE FOR INTERNAL BRACING

BY

F. H. NORTON

Aerodynamical Laboratory, National Advisory Committee for Aeronautics,
Langley Field, Va.

153215—S. Doc. 166, 66-2——48

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REPORT No. 75.

THE AERODYNAMIC PROPERTIES OF THICK AEROFOILS SUITABLE FOR INTERNAL BRACING.

By F. H. Norton.

INTRODUCTION.

The object of this investigation is the determination of the characteristics of various types of wings having sufficient depth to entirely inclose the wing bracing, and also to provide data for the further design of such sections. This type of wing is of interest—first, because it eliminates the resistance of the interplane bracing, a portion of the airplane that sometimes absorbs one-quarter of the total power required to fly; second, because it simplifies the construction and assembly of the wing structure, and, third, because these wings may be made to give a very high maximum lift. At the present time, thick internally braced sections are used with considerable success on several German machines, notably the Fokker and Junker biplanes. This type of wing was not original with the Germans, however, for an Antoinette monoplane was built and flown in France about 1910, which was entirely braced from inside the wing section. This wing was flat bottomed and had a maximum h/c ratio of one-sixth.

It was intended to investigate the following subjects:

1. Effect of changing the upper and lower camber of thick aerofoils of uniform section.
2. Effect of thickening the center and thinning the tips of a thin aerofoil.
3. Effect of adding a convex lower surface to a tapered section.
4. Effect of changing the mean thickness with constant center and tip sections.
5. Effect of varying the chord along the span.
6. Effect of varying the thickness and chord in a more complex manner.

The last subject is not yet completed and will be treated later.

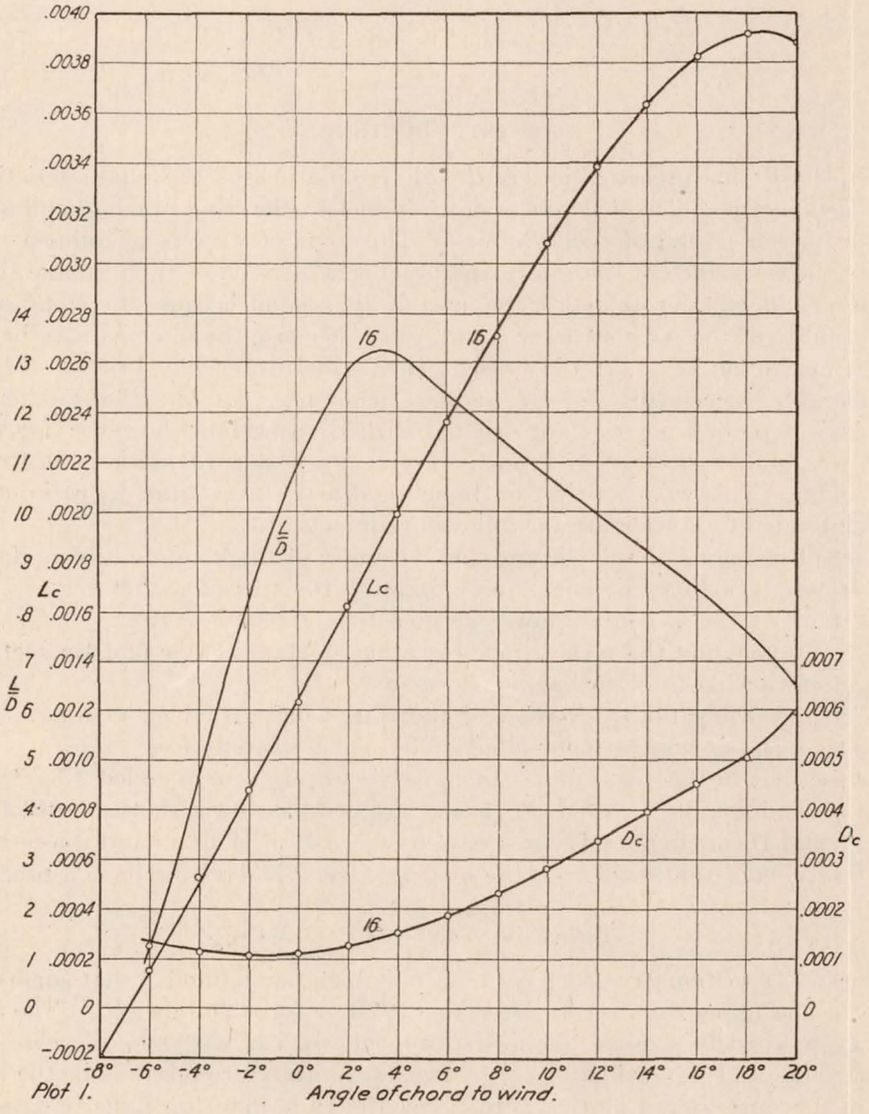
All the sections in this test unless otherwise stated are square ended 3 by 18 inch models, tested with an end spindle at 30 M. P. H. and are comparable with the tests of the U. S. A. sections. Lc and Dc are in pounds per square foot and M. P. H. units, and the center of pressure is given in fractions of the chord from the leading edge. The results have a precision of about 1 per cent.

THICK CONSTANT SECTION WINGS.

The Durand 13 section gave such an unusually high maximum lift that some slight changes were made in the upper camber to determine its best form and height. The surfaces were made of wax, scraped to size as described in report No. 74. As some of these sections were tested by students and the ordinates were not as accurately produced as in the later sections, the results of the runs are not plotted here. (See the bulletin of the Experimental Department Airplane Engineering Division, December, 1918.) They are sufficiently precise, however, to warrant general conclusions. Except for the higher and more stable maximum lift, these sections gave results that are in agreement with the N. P. L tests on varying the upper and lower camber.

On thick sections the maximum ordinate must be kept closely to one-third of the chord from the leading edge. Moving it farther back gives a flatter, but lower burble point, while moving it forward gives a lower and very unstable lift curve. With the maximum ordinate

one-third of the chord from the leading edge and a section similar to the Durand 13, the highest maximum lift is reached when the greatest thickness is about 0.477 inch on a 3-inch chord. Beyond this height, the lift curve is unstable and decreases with increase in camber. A section was tried with a thin trailing edge, but there was no improvement and the lift curve had a very bad break in it. The Durand 13 section was also tested with a Constantin type of leading edge. The lift increased rapidly to about 10°, then slowly to about 30°. The maximum Lc and the maximum L/D were not improved, however, with this change. It seems evident that the best upper camber has a maximum height of about 0.477 inch on a 3-inch chord, one-third of the way from the leading edge, giving a maximum Lc of about 0.00400 and a maximum L/D of 13.

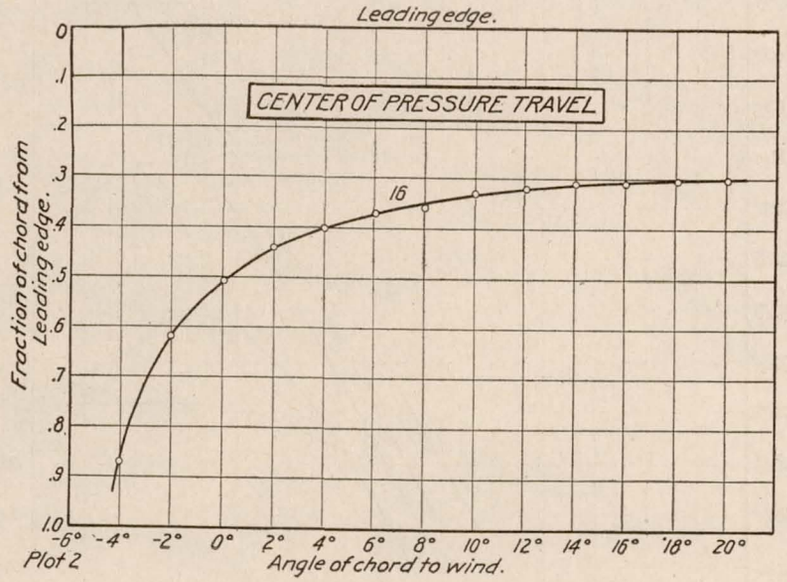


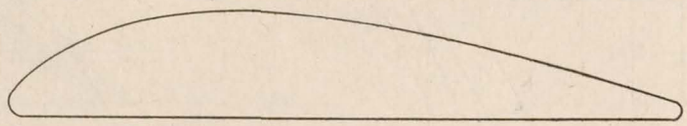
Plot 1.

The lower surface has less effect on the aerofoil than the upper. As this surface is made more convex the lift and the drag decrease until a minimum drag is reached when the section is symmetrical. The minimum drag also moves to lower angles as the lower surface is made more convex. The maximum L/D is not affected by small changes in the lower surface, but the L/D at low angles is improved by a small convex camber. One section with a concave lower surface was interesting, in that it showed a positive, but unstable, lift at $-40°$ incidence. Its maximum value for L^c was 0.00422. Several other irregular lower surfaces were tried, but showed no great improvement over the flat lower surface.

The best flat bottomed section (used as the master section, Fig. 3) seems to be No. 16, which has an h/c ratio of 0.158, a maximum Lc of (0.00392), and a maximum L/D of (13.1). The lift, drag, and L/D for this section are plotted on Plot 1 and the C. P. movement on Plot 2. To illustrate the decrease in wing area allowed by using this wing section, we may take as an example a high-powered machine weighing 4,000 pounds and having a wing area (R. A. F. 15 section) of 450 square feet, a loading of about 9 pounds per square foot. To have the same landing speed an area of 300 square feet would be sufficient with the No. 16 section.

These wings of deep constant section are satisfactory in respect to spar room and maximum lift, but the L/D is about 20 per cent lower than for the wings used at present.





MASTER SECTION

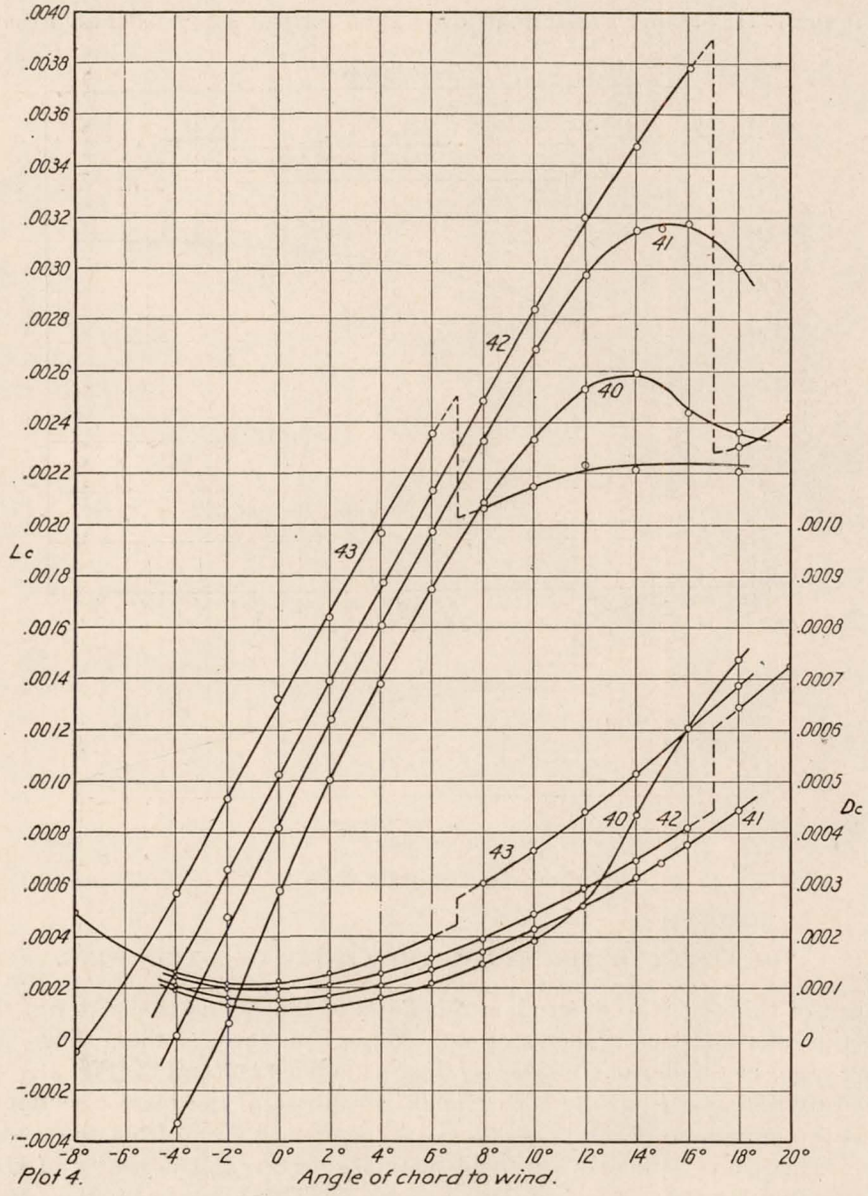
3 X Model Size Center Section for #42 and #46

FIGURE 3.

THE EFFECT OF THICKENING THE CENTER OF A THIN WING.

The object of this test is to determine the effects of thickening the center of the span, and thinning the tips, of a standard type of section. All sections through these wings, perpendicular to the leading edge, are similar to a master section, a modified Durand 13 (Fig. 3). All ordinates were obtained by reducing from the corresponding ordinate of the master section in the same proportion as the maximum ordinate is reduced by a smooth curve from the center to the tip of the wing. This curve is nearly parabolic with its vertex at the center of the span. All sections were made flat bottomed for ease in cutting. There are two series, No. 40–No. 43, where the section at the tip has a chord to depth ratio 13, and the center of the span is thickened successively, and No.44–No. 46 where the tip has a chord to depth ratio of 25 and the center is successively thickened in the same way except that the deepest section is omitted because of its obvious unsuitability as shown by No. 43. The center of the pressure travel was not plotted for sections No. 44–No. 46 because it was thought that nothing of interest would be shown. The models were constructed of maple, 3 by 18 inches and were within 0.005 inch of the ordinates given in the following tables. Lc and Dc (Plots 4 and 5) and L/D (Plots 6 and

7) are plotted against angle of incidence for each case. Where the curve was discontinued, a sharp break was made, as a fairer representation than a smooth curve. On Plot 8 the L/D is also plotted against $\frac{Lc}{Lc\ max.}$ as giving most readily the comparative merits of the various sections. A fast machine must fly at 2 to 3 times its minimum speed so that a high speed wing must have a high L/D at one-fourth to one-ninth of the maximum Lc. The center of pressure travel for sections No. 40–No. 43 is plotted in the usual manner (Plot 9). Figure 3

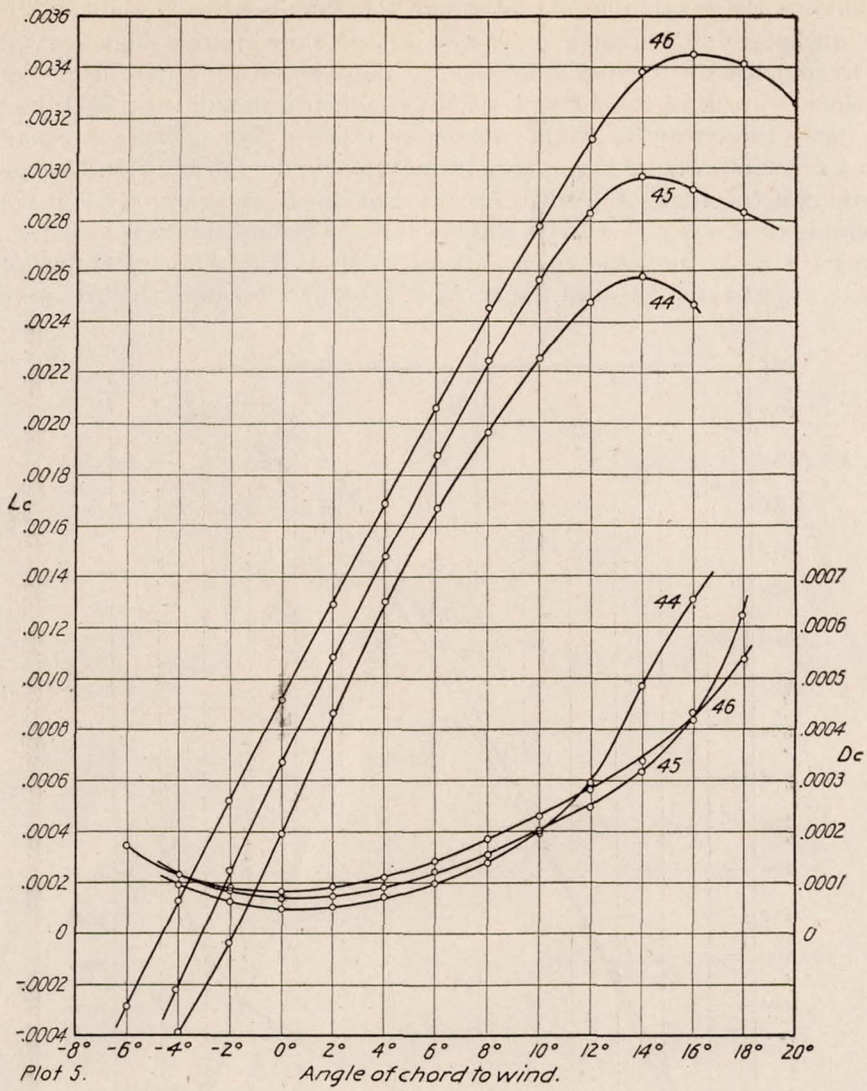


Plot 4.

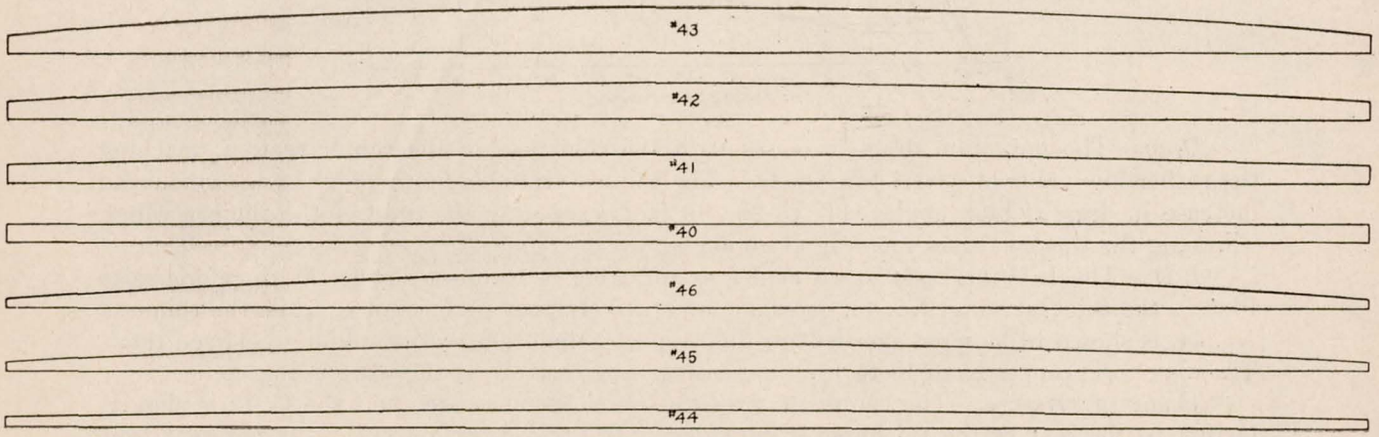
shows the master section and Figure 10 shows the front profile of the wings. Although drawn to scale, they are not intended as accurate representations of the wings, but simply to show the relative shape of the sections.

The following facts are evident from the curves:

Lift.—As the wing is thickened in the center, the lift curve shifts to the left and the maximum lift increases until h/c in the center of about 0.158 is reached, after which the flow is unstable and the maximum rapidly decreases. Thinning the tips shifts the lift curve toward the right,



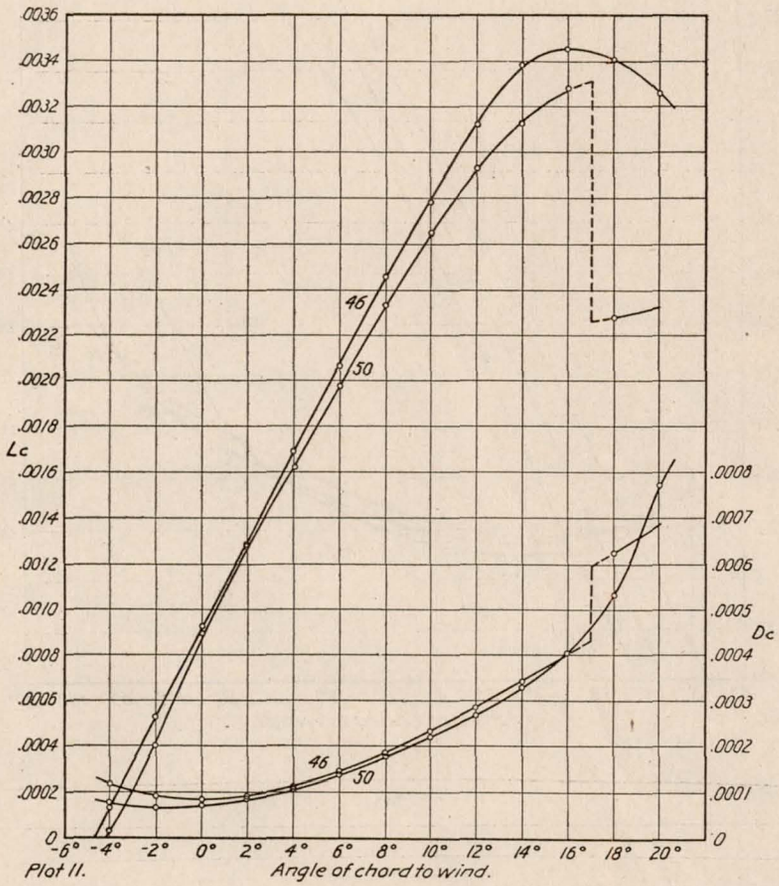
Plot 5.



MAXIMUM SECTION NORMAL TO CHORD
Full Size Chord = 3"

FIGURE 10

lowers and flattens the maximum, except where the wing is already thin, in which case the maximum is unchanged. Sections No. 42 and No. 45 show quite a high maximum, 0.00378 and 0.00345 as compared with 0.00258 for the constant section wing (No. 40). Sections No. 42 and No. 43 show a break in the air flow that is common in many thick sections. At certain angles of incidence there may be two or even more types of flow. This condition is somewhat analogous to a supersaturated solution, as a given type of flow can be carried beyond its normal point of breaking if the angle of incidence is changed slowly and carefully, but if jarred or left for a considerable time will revert to its stable value. This instability is lessened and in some cases disappears with an increase in velocity to 40 M. P. H. This instability of flow is also associated with aspect ratio, for even the R. A. F. 6 shows a break in the lift curve at very low aspect ratios.



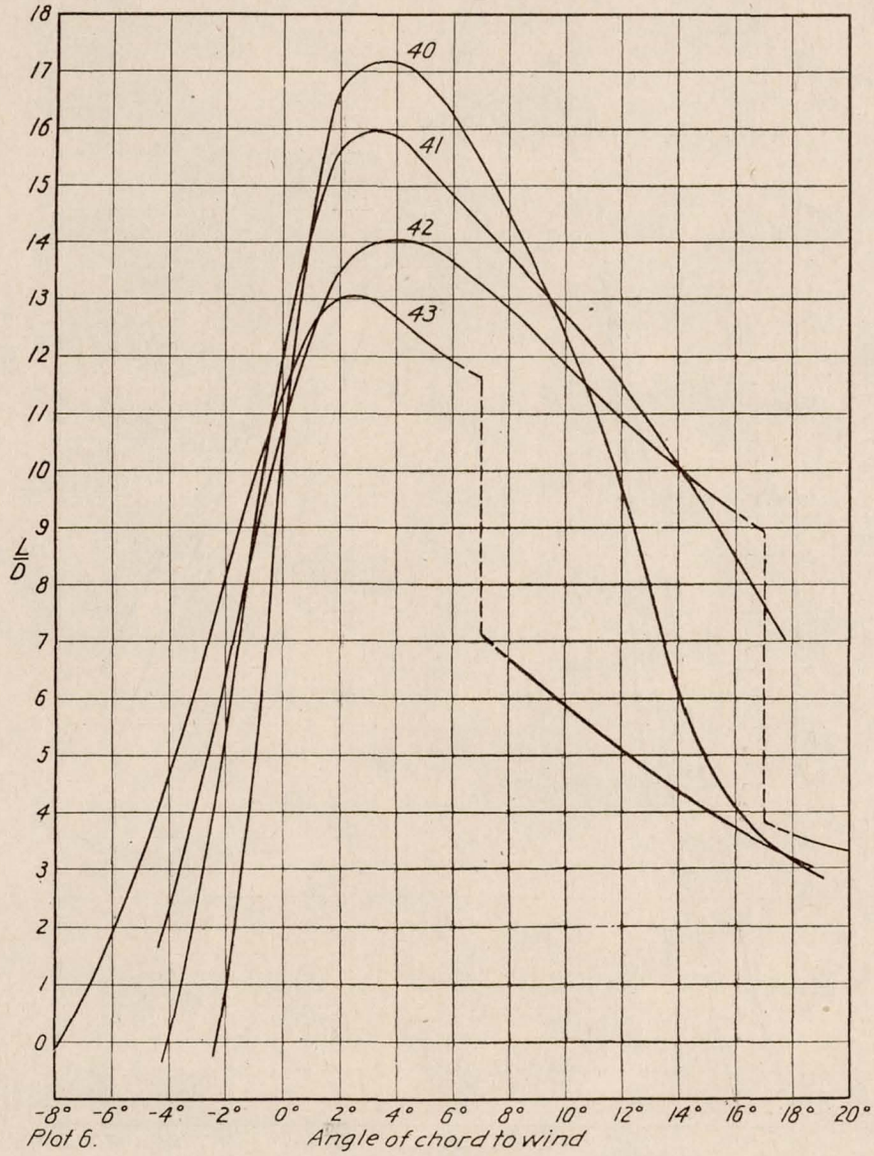
Plot II.

Drag.—The minimum drag decreases with the thickness of the center section, reaching the rather low value of 0.0048 for No. 44. The thinner sections, however, show a pronounced increase in drag at high angles, 14° to 20°, in fact, exceeding the drag of the thicker wings. Thinning the tips decreases the drag at all angles.

L/D.—The L/D increases at all angles as the wing is thinned down. With reference to Plot — the thickest wing, No. 43, gives a comparatively poor performance, while the thinnest, No. 44, is shown to be most excellent in this respect; the other sections falling between them. The max. L/D ranges from 13 to 18.2, increasing progressively as the wing is thinned.

Center of pressure.—The center of pressure travel becomes less, and the C. P. is slightly farther to the rear as the thickness is increased. The travel on No. 40 lies 28 per cent from the leading edge at 12° and 51 per cent at 0° while on No. 43 it moves, between the same angles, from 35 to 47 per cent.

This test shows that a thin flat-bottomed wing (No. 40) may be thickened in the center until an h/c ratio of 0.158 is reached (No. 42), with an increase in maximum lift of 50 per cent and a decrease in the maximum L/D of 18 per cent and in the L/D at one-ninth maximum Lc of 30 per cent. If at the same time the tip is thinned to an h/c ratio of $\frac{1}{25}$ (No. 46) the maximum lift is increased 32 per cent the maximum L/D is reduced 12 per cent and the L/D at one-ninth maximum Lc is reduced 18 per cent as compared with No. 40. The thickness can not be

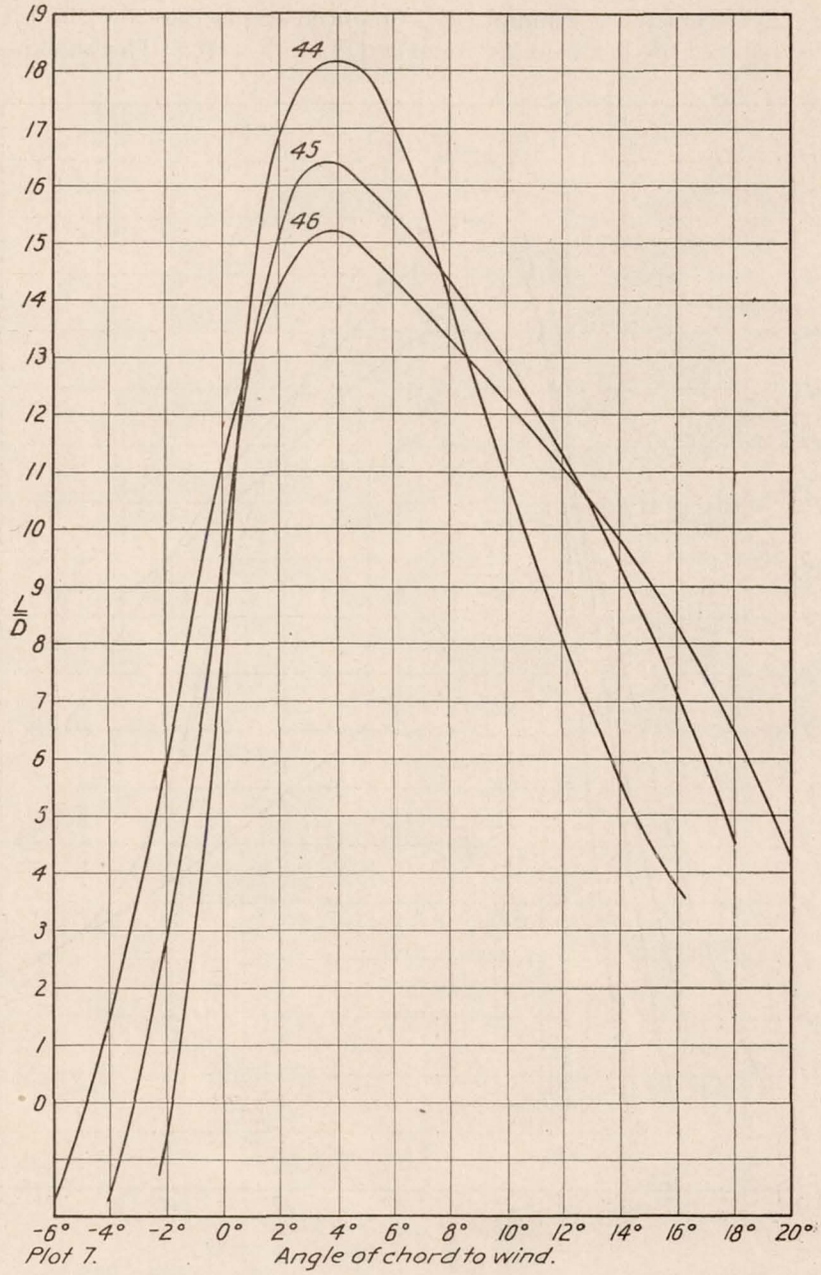


Plot 6.

increased beyond this, for the maximum Lc and L/D fall off rapidly. If a flat-bottom section (No. 40) be thinned at the tips to an h/c ratio of one-twenty-fifth (No. 44) the maximum lift is unchanged but the maximum L/D is increased 6 per cent and the L/D and one-ninth maximum Lc is increased 20 per cent. The wing is, of course, of no use for internal bracing, but is included in this report to complete the series.

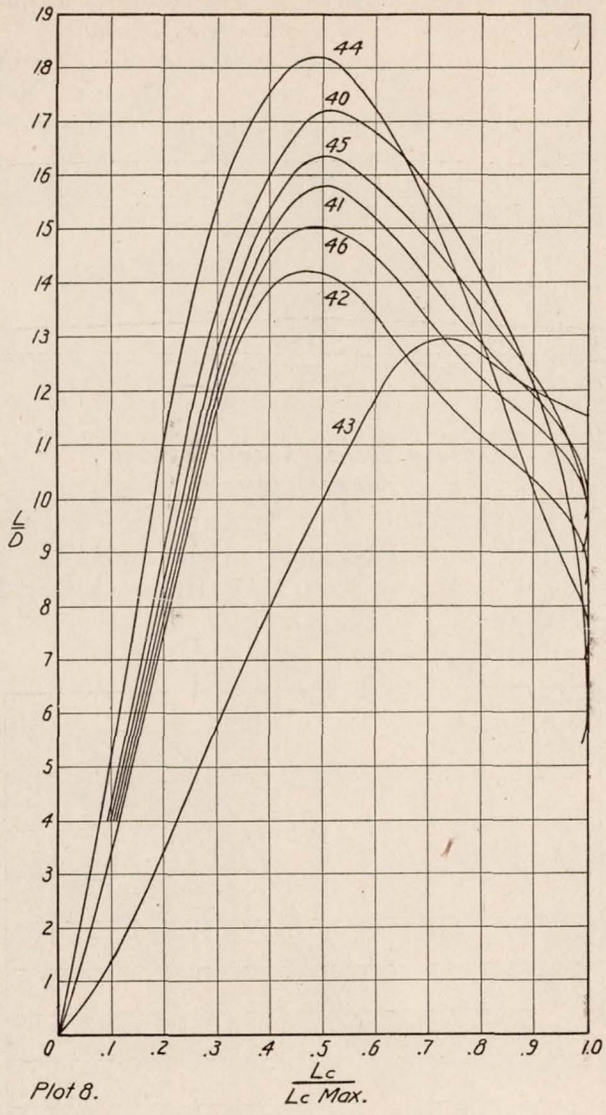
There is no particular reason why these sections should be compared to No. 44, as this was simply a reduction of the matter section to the thickness of an average wing. It happens to have a fairly good L/D and a rather low maximum lift. For a more general comparison, section

No. 46, the most practical section for internal bracing, can be compared with a high lift section, U. S. A. 2. Section No. 46 has a 7 per cent increase in maximum lift and a 3 per cent decrease in maximum L/D over the U. S. A. 2, and the L/D at one-ninth maximum Lc is 30 per cent higher on section No. 45.

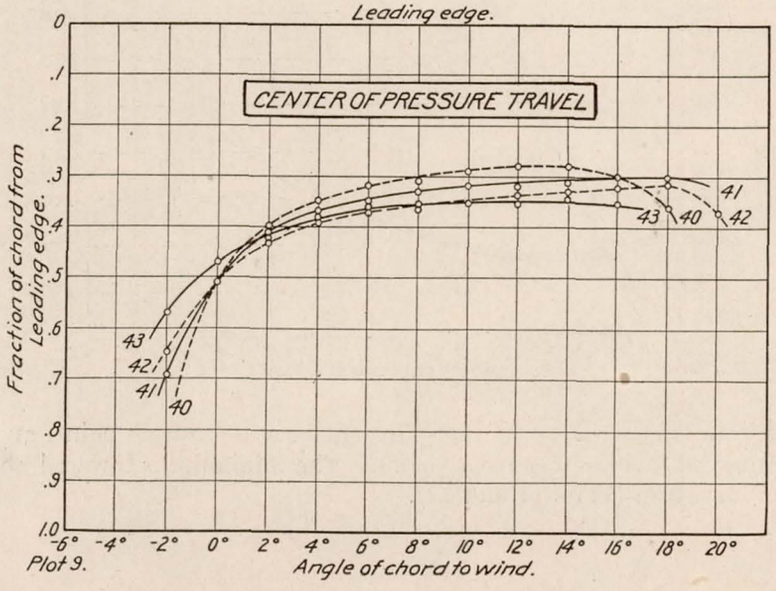


THE EFFECT OF ADDING A CONVEX LOWER SURFACE TO A THICK TAPERED WING.

As the limit of thickness is reached with a flat-bottomed section when h/c equals 0.158, it is intended to determine the effect of adding a convex lower surface to wings No. 46 and No. 51, so that the h/c ratio will be increased to one-fifth at the center (Fig. 16). These sections, No. 50 and No. 53, have the lower surface reduced in the same manner as the upper surface is reduced in going from the center to the tips. The spar room is increased 25 per cent and the


44
40
45
41
46
42
43
L/D
Lc / Lc Max.

Plot 8.

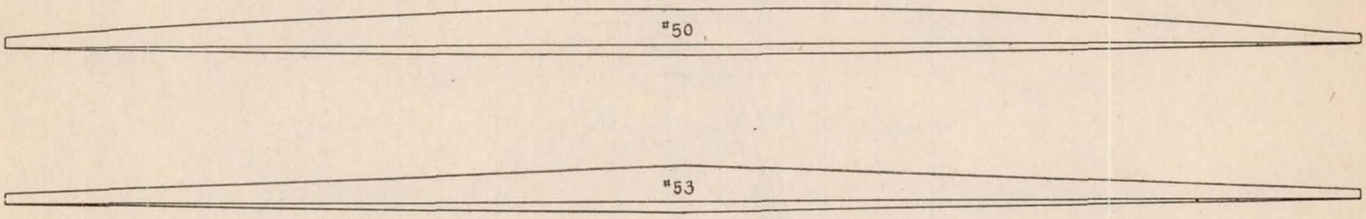

Leading edge.
CENTER OF PRESSURE TRAVEL
Fraction of chord from Leading edge.
41
43
40
42
Angle of chord to wind.

Plot 9.

general performance of the section is improved by this addition, making this one of the few changes that are both structurally and aerodynamically beneficial.

Adding a convex lower surface of this type gives the following results:

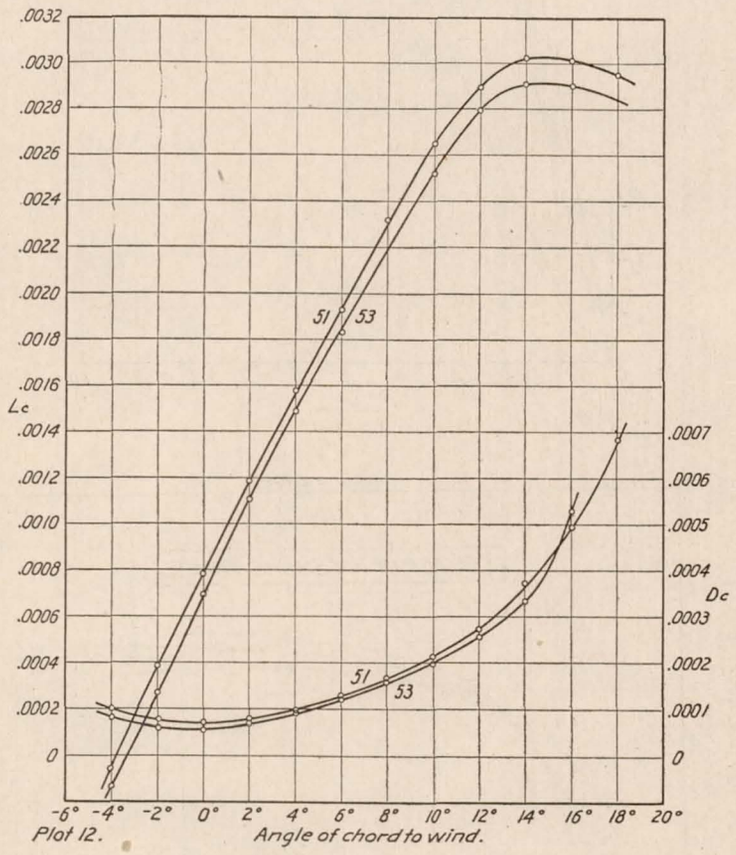
Lift.—The maximum Lc is reduced 3 to 6 per cent. The lift is reduced at all angles, but at 0° to 4° is quite high, giving a decided hump to the curve at this point. This characteristic



MAXIMUM SECTION NORMAL TO CHORD
FULL SIZE CHORD=3"

FIGURE 16.

was noticed when a convex lower surface was added to the Durand 13. Section No. 50 gave an unstable burble point at 30 M. P. H., but at 40 M. P. H. gave a very flat maximum with the same value of Lc. (Plots 11 and 12.)

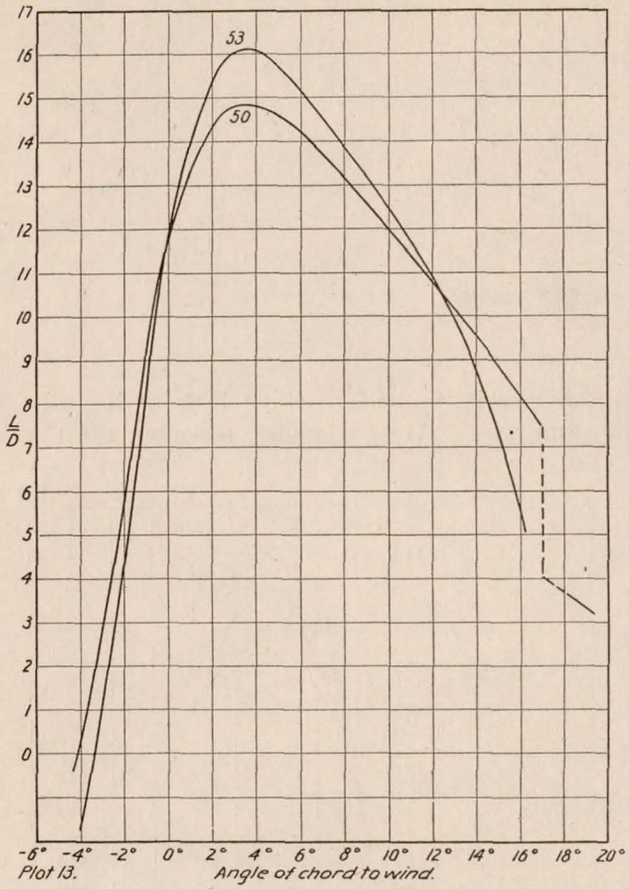


Plot 12.

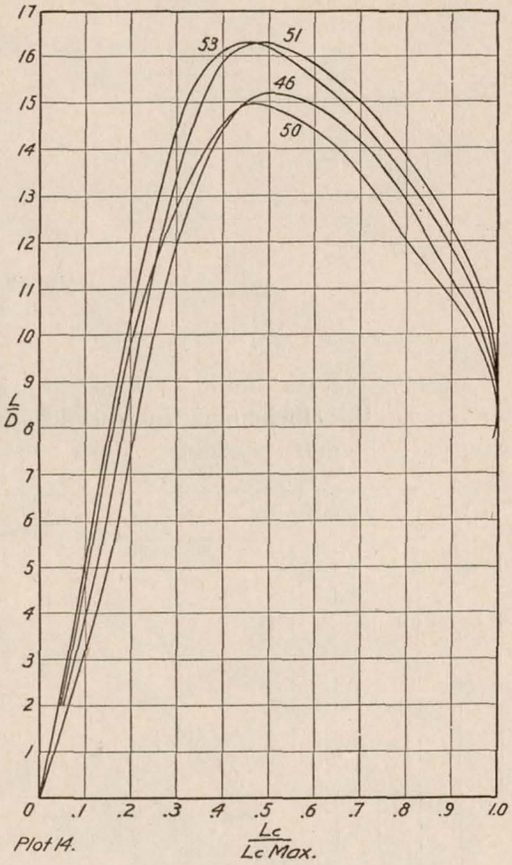
Drag.—The drag is lowered at all angles except near the burble point, and the position of the minimum is moved to more negative angles. The minimum is lowered about 20 per cent, and has a flatter curvature (Plots 11 and 12).

L/D —The maximum L/D is reduced 1 or 2 per cent, but the L/D at one-quarter maximum L^c is increased 10 per cent, and that at one-ninth maximum L^c 35 per cent (Plots 13 and 14).

Center of pressure travel.—The center of pressure travel for No. 50 is plotted in Plot 15, and shows no difference from the travel on thin sections.

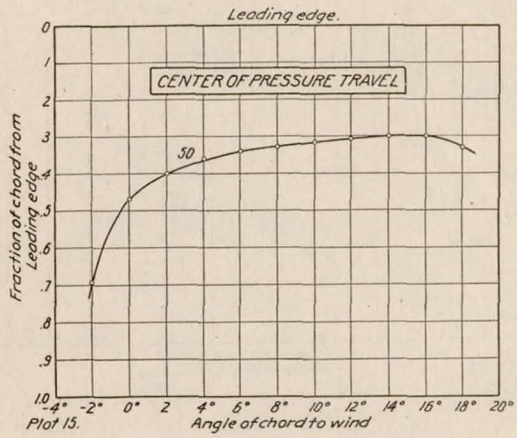


Plot 13.



Plot 14.

Both of these sections are excellent from every point of view. They allow room for ample spars (10-inch depth on a 5-foot chord), have a high maximum Lc, a maximum L/D only slightly lower than the average for thin wings, yet have an L/D at low values of Lc that is only exceeded by a few thin sections. Section No. 50 gives the higher maximum lift and the greater room for spars, but No. 53 gives the higher efficiency.



Plot 15.

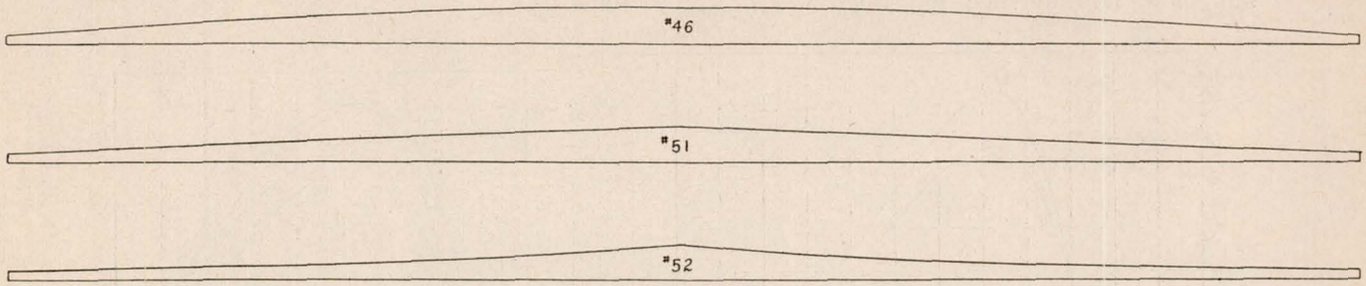
THE EFFECT OF VARYING THE MEAN THICKNESS IN A SERIES OF WINGS WITH CONSTANT TIP AND CENTER SECTIONS.

The object of this series was the determination of the effects due to thinning the wing more or less rapidly from the center to the tips. Front profiles of these sections (Nos. 46, 51, 52) are shown on figure 17.

The following facts are evident from this test:

Lift.—The lift is everywhere decreased as the section is thinned and all the sections show a flat burble point. The lift does not decrease as rapidly as the thickness, for the lift is approaching the limiting value of a flat plate. (Plot 18.)

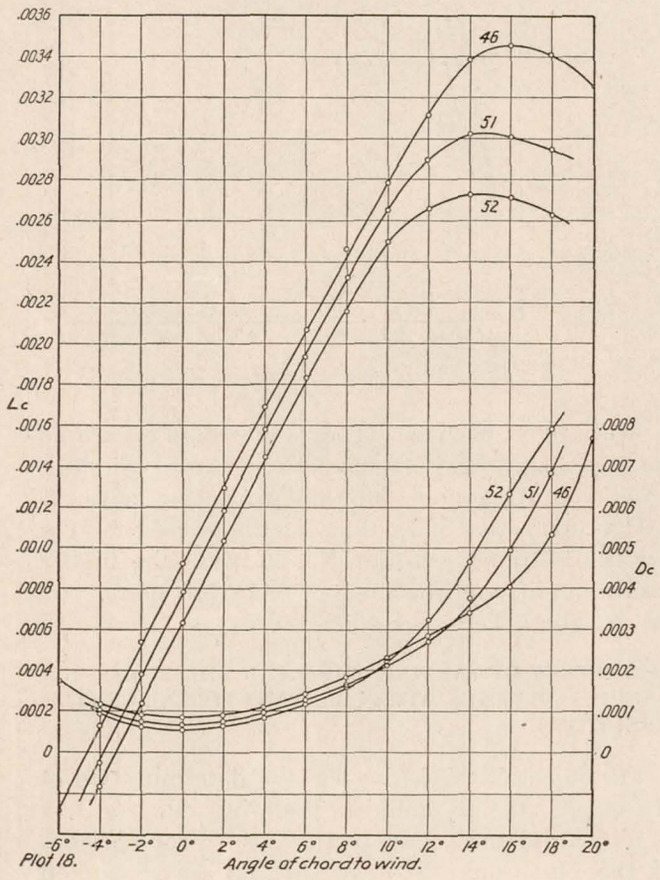
Drag.—The drag at low angles decreases with the thickness, but less rapidly as the wing becomes thinner. It is interesting to notice that above 12° the thicker wing has the least drag. (Plot 18.)



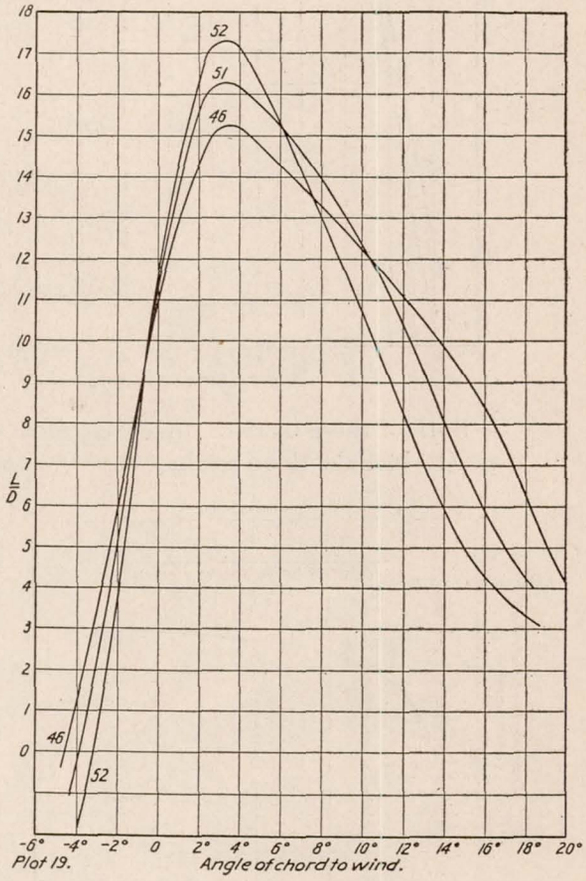
MAXIMUM SECTION NORMAL TO CHORD
Full Size. Chord = 3"

FIGURE 17

L/D.—The maximum L/D increases as the wing is thinned, reaching 17.4 for No. 52. At low angles the efficiency is increased in the same way. At high angles, however, the thicker wings are the more efficient. (Plots 19 and 20.)



Plot 18.

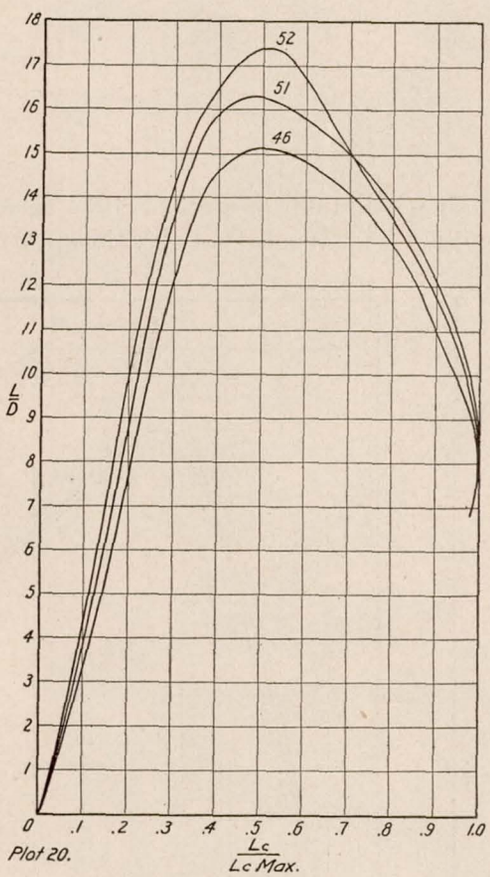


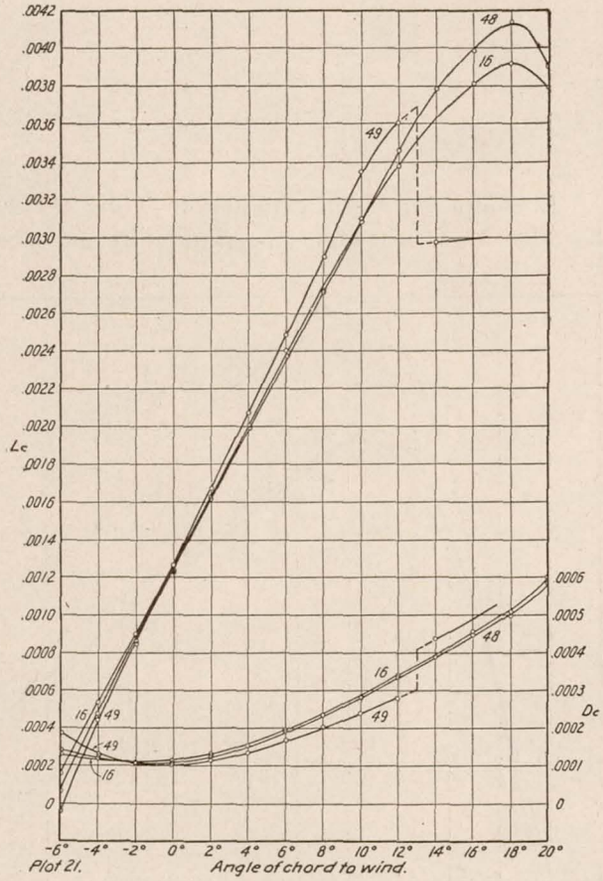
Plot 19.

Conclusions.—The results obtained from this series show that these wings have properties in general in close agreement with those of a uniform mean section. The more strongly tapered ones show, however, an evidently greater efficiency at low angles than the mean uniform section would indicate.

WINGS WITH VARYING CHORD.

The wind tunnel investigations of wings that have a chord which varies along the span is a rather difficult problem, because of the great alteration in the properties of similar aerofoils, when the chord is changed. It seems evident, at least with thick sections, that the chord can not be reduced to less than 2 inches at 30 M. P. H. without introducing a break in the air flow that materially reduces the value of the maximum lift. For instance, a wing with a 2-inch chord at the tip and a 3-inch mean chord, gives a uniformly better performance than a similar constant section wing, but if the tip is reduced to $1\frac{3}{4}$ inches, with the same mean chord, the performance is markedly inferior to the constant section wing. Again, section No. 49 (Plots 21, 22, 23), having a 24-inch span and a $1\frac{1}{2}$-inch chord at the tip, gave a maximum Lc 0.00360, but when





3 inches were cut off of each tip, leaving an 18-inch span and a 2-inch chord at the tip (Fig. 24), the maximum Lc was increased to 0.00413. This does not prove, however, that on a full-sized machine, where the LV is large, a small chord at the tip is a disadvantage.

For this same reason it seems probable that wind-tunnel tests on wings with raked and rounded tips, although showing a considerable advantage over a square tip, do not show as comparatively great an improvement as actually occurs on the full-sized machine. In order to investigate this matter fully, a series of similar sections should be tested with the greatest possible range in LV.

This subject of varying the chord was taken up not so much with the hope of improving the aerodynamic properties of the wing, but because of the structural advantages possessed by this type of wing. When the chord is diminished at the tip and increased at the center, not only is the spar depth increased at the center, but the center of lift of the wing is brought closer to the

body, thus decreasing the bending moment in the spars. If the wing is tapered sufficiently, the spars can be brought together at the tips as in the German Ago, simplifying and increasing the rigidity of the drag truss.

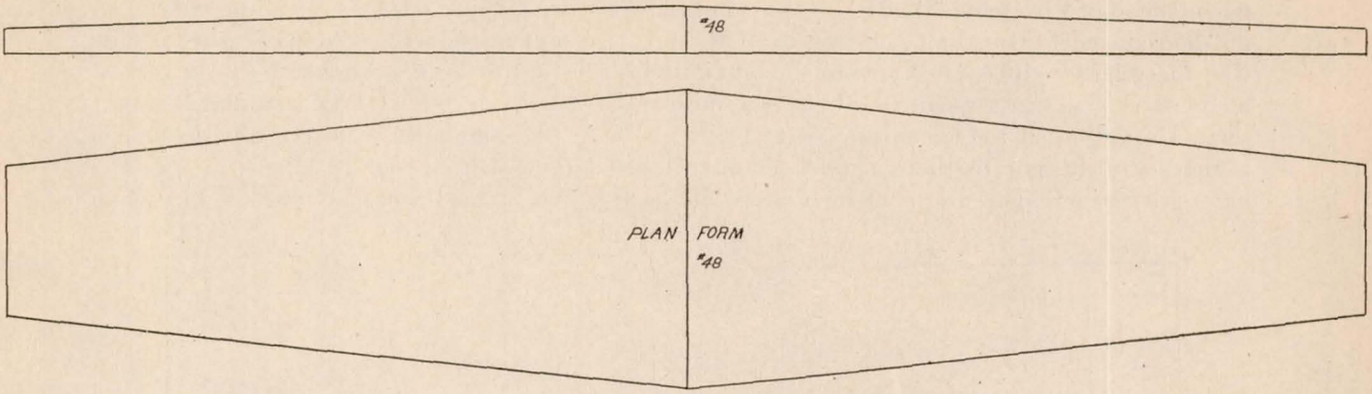
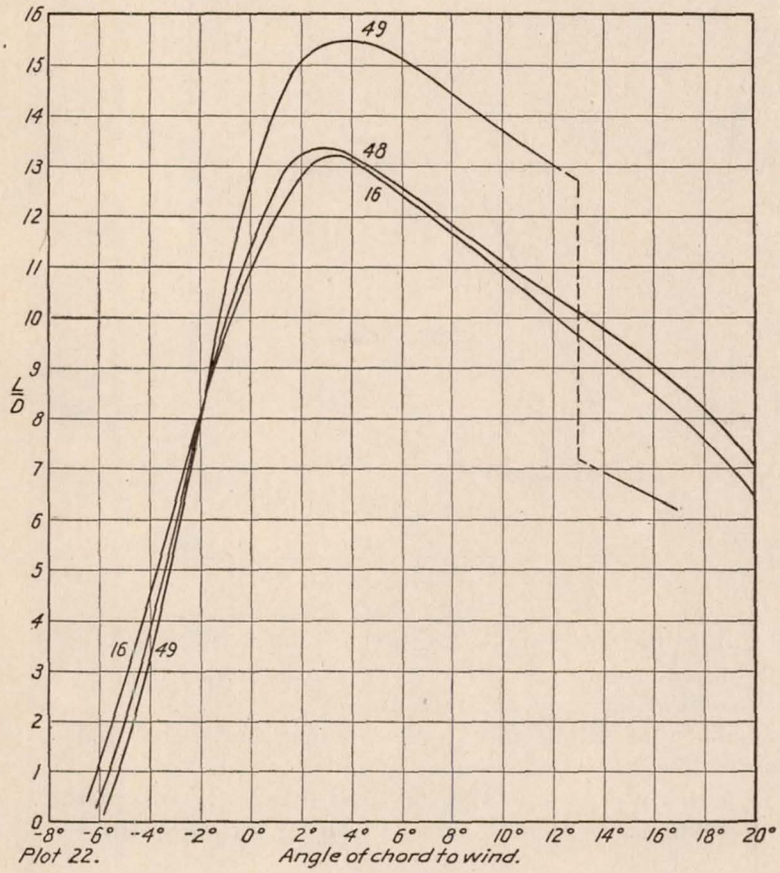
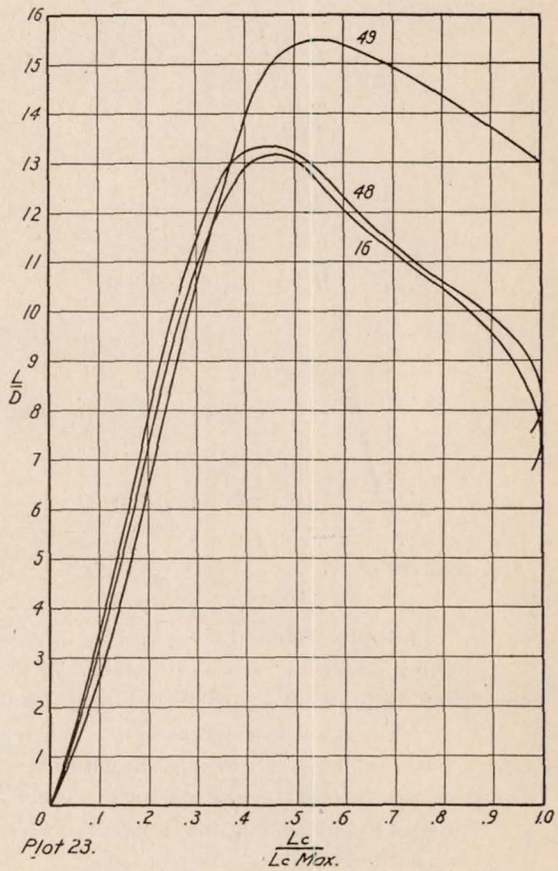


FIGURE 24.

In comparing sections 16 and 48 (Plots 21, 22, 23) it is seen that the section with a varying chord has 5 per cent higher maximum lift and substantially the same L/D at all points. When



Plot 22.



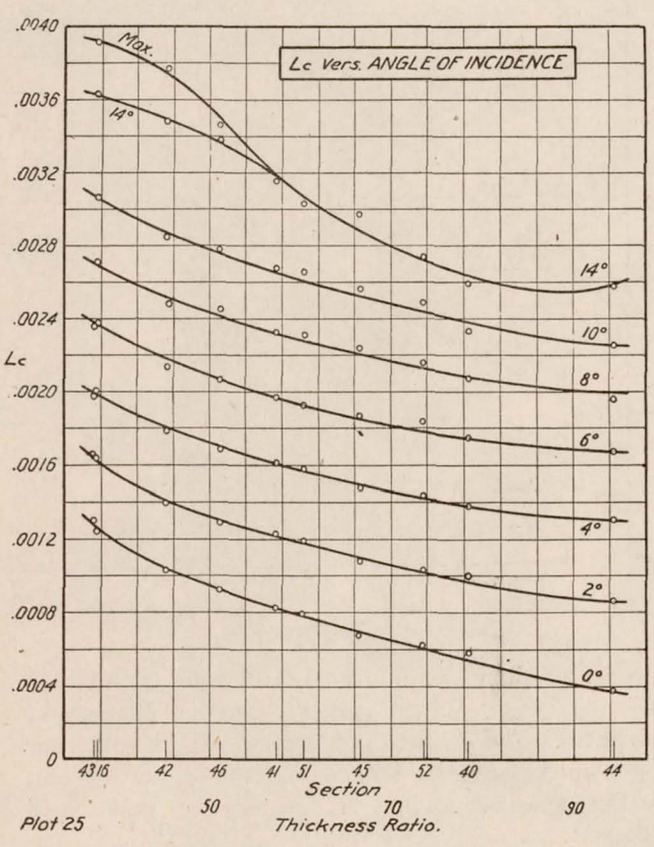
Plot 23.

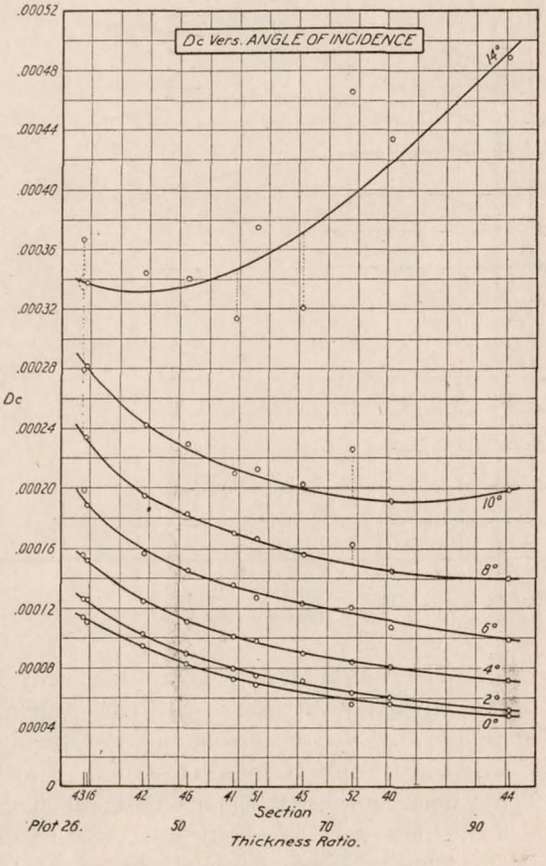
the L/D is plotted against $\frac{\text{Lc}}{\text{Lc Max.}}$ it is evident that the constant section wing is inferior in efficiency at every point. There was time for only a very limited study of this subject, but the results show enough promise to deserve further investigation.

SUMMARY.

It is a rather difficult matter to compare the properties of the different sections tested because of the number of variables present. It was thought that a comparison could be best made by plotting the mean thickness of the wing against the Lc, Dc, and L/D for various angles of incidence, and against L/D for various values of Lc. Instead of using the actual thickness of the wing the ratio of the span to the mean thickness is used, and will be termed thickness ratio. In this report the term will be applied only when the aspect ratio is six. Another characteristic of the wing is the ratio of the mean thickness of the wing to the maximum thickness, or amount of taper. These characteristics for a number of the wings are tabulated below:

Wing No.	Mean thickness.	Thickness ratio.	Mean ord. / Max. ord.
40	0.230	78.3	1.000
41	.314	57.3	.980
42	.399	45.1	.837
43	.483	37.3	.805
44	.191	94.3	.830
45	.271	66.5	.768
46	.351	51.3	.737
51	.298	60.4	.625
52	.245	73.4	.535
16	.477	37.6	1.000



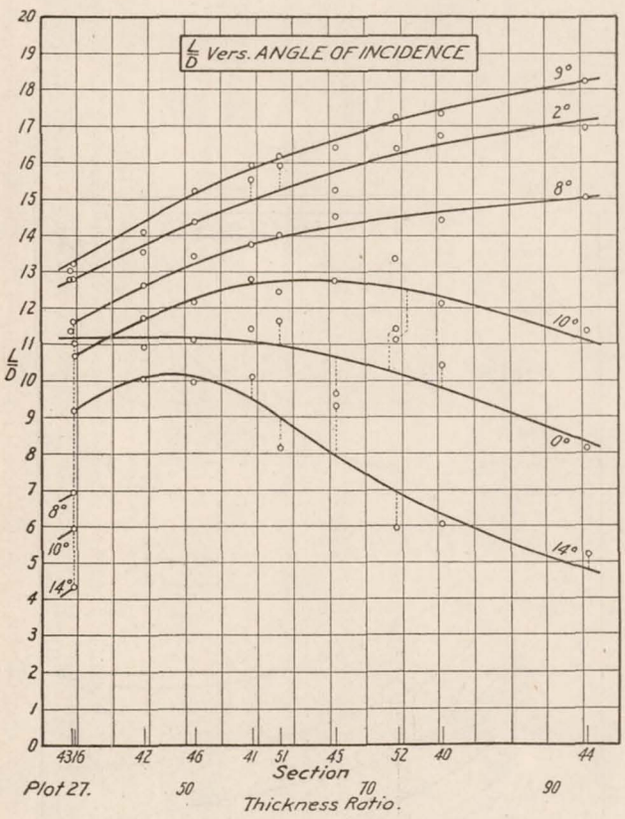


On plots 25 to 28 the properties of these wings are plotted against thickness ratio. It was not expected that the points would lie on a smooth curve, but it was hoped that there would be enough regularity to determine a mean line, from which the deviation of the points could be studied.

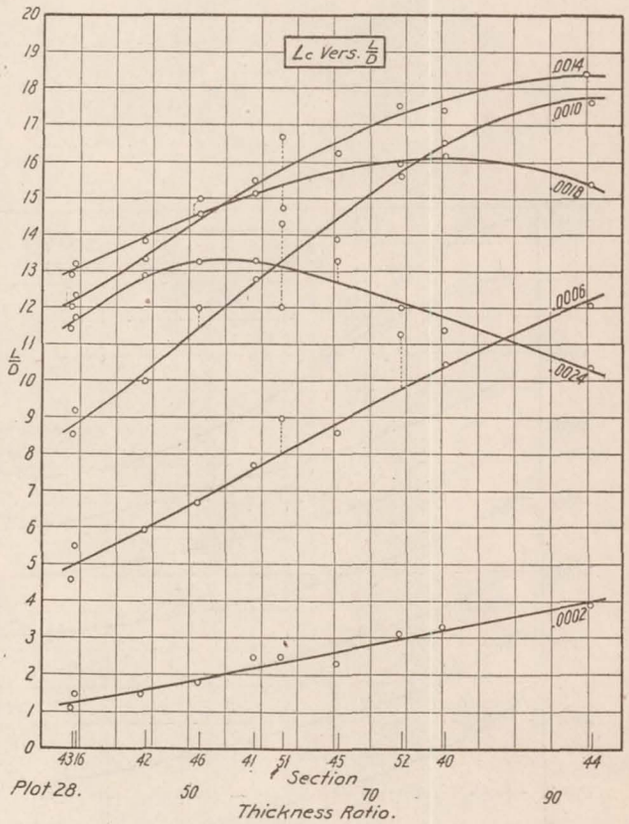
153215—S. Doc. 166, 66-2——49

It is seen from plot 25 that the lift coefficient decreases with an increase of thickness ratio, and of course will approach the values for a flat plate. As the thickness ratio is decreased below 50 the Lc at low angles begins to increase rapidly, but at high angles increases less rapidly and at the highest lift has reached a maximum at about 37. It is interesting to notice that wings Nos. 43 and 16, having practically the same mean thickness, lie closely together up to 6°, after which the flow breaks on the former and its lift values at high angles are very low. All the other points lie closely to the mean curves and show nothing of interest.

On plot 26 it is seen that the drag at low angles increases as the thickness ratio decreases, but at 10° the drag is a minimum when the thickness ratio is 80, and at 14° when it is 50. At low angles the drag is quite regular, but at high angles the points do not lie on a smooth curve. As would be expected, wing No. 43 has abnormally high values of drag above 6°, but below this agrees well with No. 16. Wing No. 52, and to a lesser extent No. 51, show an unusually low drag at small angles and a large drag at high angles. From the table above it will be noticed that these two wings have the greatest taper of any.



Plot 27.



Plot 28.

The points on plot 27 are naturally less regular than on the others, but it is evident that the efficiency increases with the thickness ratio between 2° and 8°, but at lower and higher angles it occurs at a lower thickness ratio. The efficiency is higher with the thicker wings at 0° only because this angle is farther from the angle of zero lift on the thick wings and not because these wings are more efficient at high speeds. At high angles, however, wings with a thickness ratio of about 50 are the most efficient.

This is shown more clearly on plot 28 where the efficiency is plotted against thickness ratio for various values of Lc. For low values of Lc the efficiency increases steadily with the thickness ratio, but at Lc of 0.0014 the efficiency reaches a maximum, which moves to lower values of thickness ratio as the Lc increases. Again Nos. 52 and 51 show an abnormally high efficiency at low and medium values of Lc. No. 16 shows a slightly higher L/D at all angles than No. 43.

It may be concluded from these curves that the aeodynamic properties of a series of similar wings depend in a regular way on the mean thickness, no matter what the taper. It seems possible then to predict the properties of any varying section wing with fair accuracy from a study of similar constant section wings. It is impossible, however, to exceed at any point of the wing an h/c ratio of 0.159 without exceeding the critical value. Therefore, in order to obtain the highest maximum lift, the wing should be of constant section. Wings that have a considerable degree of taper appear to have better high-speed properties than uniform section wings. This improvement is not very large but is well outside the experimental error.

In order to show clearly the relative properties of the various sections tested and their relation to the usual types of wings, their more important characteristics are tabulated below, together with a few repersentative thin sections:

Section No.	Maximum Lc.	Maximum L/D.	L/D at ¾ maximum Lc.	L/D at ½ maximum Lc.	Lc at maximum L/D.	L/D at maximum Lc.	Minimum Dc.	Maximum h/c.
40	0.00259	17.2	11.5	4.8	0.00134	6.0	0.000056	0.077
41	.00318	15.9	10.2	4.2	.00150	9.6	.000072	.118
42	.00378	14.1	9.6	3.8	.00176	9.3	.000095	.159
43	.00236	13.0	4.6	1.5	.00197	12.0	.000109	.200
44	.00258	18.2	13.6	5.8	.00125	5.5	.000048	.077
45	.00297	16.4	10.6	4.4	.00141	9.0	.000070	.118
46	.00345	15.2	9.8	4.0	.00166	8.3	.000083	.159
50	.00328	14.9	11.5	5.2	.00155	7.9	.000066	.200
51	.00302	16.2	11.5	4.5	.00158	5.7	.000067	.159
52	.00272	17.3	12.5	5.0	.00144	8.7	.000054	.159
53	.00292	16.2	12.6	5.7	.00145	7.6	.000057	.200
48	.00413	13.3	10.0	3.9	.00200	8.2	.000108	.212
16	.00392	13.2	9.0	3.6	.00188	6.9	.000108	.159
R. A. F. 6	.00304	16.6	11.0	4.2	.00129	6.9	.000068	.068
R. A. F. 15	.00269	15.8	13.0	6.3	.00103	9.5	.000048	.057
U. S. A. 2	.00322	15.7	8.8	3.1	.00162	9.3	.000088	.063
U. S. A. 1	.00278	16.7	12.3	5.4	.00139	9.6	.000056	.057

In comparison with the usual types of thin sections a thick uniform section like No. 16 shows the following differences:

1. Thick sections may give 50 per cent higher maximum lift.
2. Thick sections are more likely to give an unstable flow at large angles of incidence.
3. On thick sections the angle of no lift occurs at lower angles of incidence and the burble point at higher angles, thus extending the angular flying range.
4. Thick sections have a flatter drag curve; that is, the minimum drag is higher, but Dc rises less rapidly on either side of the minimum.
5. The L/D curve for thick sections is flatter than for thin sections, rising to a lower maximum, but holding a value close to its maximum at high and low angles of incidence.
6. The center of pressure travel of thick sections is further to the rear and of less extent than on thin sections.
7. Thick sections are more efficient at high angles of incidence.

The best tapered sections give lower maximum L/D than the thin sections, but the efficiency at all other points is as good.

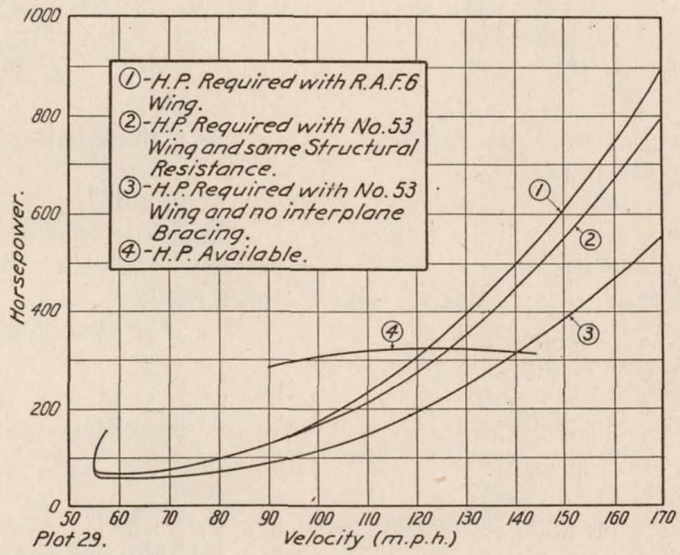
By tapering the wing both in plan form and thickness it should be possible to construct a wing which has an h/c ratio in the center (mean chord) of 0.270 and aerodynamic properties comparing quite favorably with the thin sections used now. This thickness would make possible the use of 14-inch spars on a 5-foot mean chord. A tapered wing has the advantage of having the greater part of the lift on the portion of the wing close to the body, due both to the greater area and to higher lift sections at this part of the wing, thus decreasing the bending moment in the spars.

To illustrate the value of thick wings on a machine, the performance is plotted for a 400 H. P. 3,600-pound biplane, using first a R. A. F. 6 section with the usual wing bracing, second, section 53 with the same bracing, and third, 53 without external bracing. No corrections were added to the data from wind tunnel tests, as only comparative results were required.

Section loading (coefficient of parasite resistance).	R. A. F. 6, 9.1 pounds, square feet 0.036.		No. 53, 8.8 pounds, square feet 0.036.		No. 53, 8.8 pounds, square feet 0.017.	
	(Velocity in M. P. H.)	(H. P. required.)	(Velocity in M. P. H.)	(H. P. required.)	(Velocity in M. P. H.)	(H. P. required.)
2	230	3,590	180	950	180	650
0	128	370	113	228	113	155
2	92	131	90	125	90	89
4	79	93	77	89	77	66
8	63	68	64	69	64	56
12	56	65	56	66	56	57
16	55	92	55	81	55	72

From the H. P. curves plotted below (Plot 29), assuming a curve of available H. P., the following summary is obtained:

Section.	Maximum speed.	Minimum power.	Climb.
R. A. F. 6	122 M. P. H.	65 H. P.	1,470 feet per min.
No. 53	126 M. P. H.	66 H. P.	1,470 feet per min.
No. 53	140 M. P. H.	56 H. P.	1,750 feet per min.



Plot 29.

Compared with the R. A. F. 6, No. 53 section under the same conditions of structural resistance gives the same power to climb and increases the maximum speed 4 M. P. H. Without interplane bracing this section increases the climb about 20 per cent and the maximum speed from 122 to 140 M. P. H.

It seems evident from these tests on models that wings may be designed with ample room for cantilever spars and have at the same time aerodynamic properties comparing favorably with the thin sections used now.

This subject of varying section wings is so large that only a beginning has been made in this report, for there is an almost infinite number of variables to study. The results, however, show enough promise to warrant further research with wings in which the chord and thickness are varied in a more complex manner. The thick tapered wings should also be tested on full-sized machines.

Ordinates for No. 40.

Chord station.		Chord station.	
00	0.044	120	0.228
10	.094	140	.221
20	.132	160	.207
30	.160	180	.190
40	.181	200	.170
50	.186	220	.147
60	.207	240	.122
70	.216	260	.094
80	.223	280	.065
90	.228	300	.032
100	.230		

The lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates for No. 41.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
00	0.070	0.067	0.064	0.057	0.044
10	.145	.140	.132	.118	.094
20	.202	.196	.185	.165	.132
30	.246	.238	.225	.200	.160
40	.278	.270	.254	.227	.181
50	.301	.292	.275	.245	.196
60	.318	.309	.291	.260	.207
70	.333	.323	.304	.271	.216
80	.343	.333	.313	.280	.223
90	.350	.339	.319	.285	.228
100	.353	.343	.323	.288	.230
120	.350	.339	.319	.285	.228
140	.340	.329	.310	.277	.221
160	.318	.309	.291	.260	.207
180	.292	.283	.267	.238	.190
200	.263	.255	.239	.213	.170
220	.226	.219	.207	.184	.147
240	.187	.181	.171	.152	.121
260	.144	.140	.132	.118	.094
280	.100	.097	.091	.081	.065
300	.050	.049	.046	.041	.032

This lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates for No. 42.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
0	0.095	0.091	0.083	0.069	0.044
10	.195	.187	.170	.142	.094
20	.273	.261	.240	.199	.132
30	.332	.319	.290	.242	.160
40	.375	.359	.328	.273	.181
50	.406	.389	.355	.296	.196
60	.430	.412	.376	.313	.207
70	.449	.430	.393	.327	.216
80	.463	.442	.405	.337	.223
90	.472	.452	.414	.344	.228
100	.477	.457	.417	.348	.230
120	.472	.452	.412	.344	.228
140	.458	.439	.402	.334	.221
160	.430	.412	.376	.313	.207
180	.394	.377	.345	.287	.190
200	.353	.338	.309	.257	.170
220	.305	.292	.267	.222	.147
240	.252	.242	.221	.183	.122
260	.195	.187	.171	.142	.094
280	.134	.128	.117	.098	.065
300	.068	.064	.060	.049	.032

The lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates for No. 43.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
00	0.119	0.113	0.107	0.081	0.044
10	.245	.233	.208	.165	.094
20	.344	.327	.293	.232	.132
30	.417	.397	.354	.281	.161
40	.472	.448	.401	.318	.181
50	.511	.485	.434	.345	.196
60	.541	.514	.460	.364	.207
70	.565	.536	.480	.381	.216
80	.582	.553	.495	.393	.223
90	.594	.564	.505	.402	.228
100	.600	.570	.510	.405	.230
120	.594	.564	.505	.402	.228
140	.577	.547	.490	.389	.222
160	.541	.514	.460	.366	.207
180	.495	.472	.421	.334	.190
200	.444	.422	.377	.300	.170
220	.384	.365	.326	.259	.147
240	.317	.301	.269	.214	.122
260	.245	.233	.208	.165	.094
280	.169	.160	.144	.113	.065
300	.084	.080	.072	.057	.032

The lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates for No. 44.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
00	0.044	0.042	0.037	0.031	0.024
10	.094	.089	.080	.067	.049
20	.132	.125	.112	.094	.069
30	.160	.152	.136	.113	.084
40	.181	.172	.154	.128	.094
50	.196	.186	.167	.139	.102
60	.207	.196	.176	.147	.108
70	.216	.204	.184	.153	.113
80	.223	.211	.190	.158	.117
90	.228	.216	.194	.162	.119
100	.230	.218	.196	.163	.120
120	.228	.216	.194	.162	.119
140	.221	.209	.188	.157	.116
160	.207	.196	.176	.147	.108
180	.190	.180	.162	.135	.099
200	.170	.161	.145	.120	.089
220	.147	.139	.126	.104	.077
240	.122	.115	.104	.086	.063
260	.094	.089	.080	.067	.049
280	.065	.062	.055	.046	.034
300	.032	.031	.027	.023	.017

Ordinates for No. 45.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
00	0.070	0.065	0.056	0.042	0.024
10	.145	.134	.115	.087	.049
20	.202	.189	.161	.121	.069
30	.246	.228	.196	.148	.084
40	.278	.258	.221	.167	.094
50	.301	.279	.240	.180	.102
60	.318	.296	.253	.191	.108
70	.333	.309	.263	.200	.113
80	.344	.318	.273	.206	.117
90	.350	.324	.279	.210	.119
100	.353	.327	.281	.212	.120
120	.350	.324	.278	.210	.119
140	.340	.313	.271	.204	.116
160	.318	.295	.253	.191	.108
180	.292	.270	.232	.175	.099
200	.261	.242	.207	.158	.089
220	.226	.210	.180	.136	.077
240	.187	.174	.149	.112	.063
260	.144	.133	.115	.087	.049
280	.100	.093	.079	.060	.034
300	.050	.046	.040	.030	.017

The lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates for No. 46.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
0	0.095	0.087	0.073	0.052	0.024
10	.195	.179	.150	.108	.049
20	.273	.250	.211	.150	.069
30	.332	.305	.256	.183	.084
40	.375	.344	.289	.206	.094
50	.406	.373	.312	.223	.102
60	.430	.395	.331	.236	.108
70	.449	.413	.346	.247	.113
80	.463	.425	.356	.254	.117
90	.472	.433	.363	.259	.119
100	.477	.437	.367	.262	.120
120	.472	.433	.363	.259	.119
140	.458	.420	.353	.252	.116
160	.430	.395	.331	.236	.108
180	.394	.361	.303	.217	.099
200	.353	.324	.271	.194	.089
220	.305	.280	.235	.168	.077
240	.252	.231	.194	.139	.063
260	.195	.179	.150	.107	.049
280	.134	.123	.103	.074	.034
300	.068	.062	.052	.037	.017

The lower surface is plane and ordinates given are the distances of the upper surface above this in inches.

Ordinates of undersurface No. 50.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
0	0.000	0.000	0.000	0.000	0.000
10	.023	.020	.016	.009	.000
20	.042	.035	.029	.016	.000
30	.060	.052	.041	.023	.000
40	.074	.064	.051	.029	.000
50	.090	.079	.062	.035	.000
60	.100	.087	.069	.039	.000
70	.109	.096	.075	.043	.000
80	.116	.101	.080	.045	.000
90	.121	.106	.084	.047	.000
100	.123	.109	.085	.048	.000
120	.121	.106	.084	.047	.000
140	.118	.103	.082	.046	.000
160	.110	.097	.076	.430	.000
180	.100	.087	.069	.039	.000
200	.087	.076	.060	.034	.000
220	.073	.064	.050	.029	.000
240	.058	.050	.040	.022	.000
260	.040	.035	.028	.016	.000
280	.020	.017	.014	.008	.000
300	.000	.000	.000	.000	.000

Ordinates below chord line upper surface same as No. 46.

Ordinates for No. 51.

Chord station.	Distance from center of span in inches.		Chord station.	Distance from center of span in inches.	
	0	9		0	9
0	0.095	0.024	120	0.472	0.119
10	.195	.049	140	.458	.116
20	.273	.069	160	.430	.108
30	.332	.084	180	.394	.099
40	.375	.094	200	.353	.089
50	.406	.102	220	.305	.077
60	.430	.108	240	.252	.063
70	.449	.113	260	.195	.049
80	.463	.117	280	.134	.034
90	.472	.119	300	.068	.017
100	.477	.120			

Straight line between center section and tip. Undersurface flat.

Ordinates for No. 52.

Chord station.	Distance from center of span in inches.				
	0	3	5	7	9
0	0.095	0.055	0.038	0.027	0.024
10	.195	.113	.077	.056	.049
20	.273	.159	.108	.078	.069
30	.332	.193	.132	.095	.084
40	.375	.218	.149	.107	.094
50	.406	.236	.161	.116	.102
60	.430	.250	.170	.123	.108
70	.449	.261	.178	.128	.113
80	.463	.269	.184	.132	.117
90	.472	.274	.187	.134	.119
100	.477	.277	.189	.136	.120
120	.472	.274	.187	.134	.119
140	.458	.267	.182	.131	.116
160	.430	.250	.170	.123	.108
180	.394	.229	.156	.113	.099
200	.353	.205	.140	.102	.089
220	.305	.177	.121	.088	.077
240	.252	.147	.100	.072	.063
260	.195	.113	.078	.056	.049
280	.134	.078	.053	.038	.034
300	.068	.040	.027	.019	.017

The lower surface is plane and the ordinates given are the distances above this in inches.

Ordinates for undersurface for No. 53.

Chord station.	Distance from center of span in inches.		Chord station.	Distance from center of span in inches.	
	0	9		0	9
0	0.000	0.000	120	0.121	0.000
10	.023	.000	140	.118	.000
20	.042	.000	160	.110	.000
30	.060	.000	180	.100	.000
40	.074	.000	200	.087	.000
50	.090	.000	220	.073	.000
60	.100	.000	240	.058	.000
70	.109	.000	260	.040	.000
80	.116	.000	280	.020	.000
90	.121	.000	300	.000	.000
100	.123	.000			

Upper surface the same as No. 51.

REPORT No. 76

FUSELAGE STRESS ANALYSIS

BY

EDWARD P. WARNER and ROY G. MILLER

Aerodynamical Laboratory, National Advisory Committee for Aeronautics
Langley Field, Va.

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REPORT No. 76.

FUSELAGE STRESS ANALYSIS.

By Edward P. Warner and Roy G. Miller.

INTRODUCTION.

There is, at the present time, a wide diversity in the methods employed by designers for analyzing the stresses in a fuselage of the built-up type in which the shear is taken by diagonal bracing wires, and there is a similar diversity of opinion as to the best type of analysis manifested in the standards and specifications issued by various governmental agencies.

In a specification for pursuit machines (No. 1003) issued by the Signal Corps just after the United States entered the war, the requirement is that the fuselage be designed to stand a dynamic load factor of 5 and a tail load of 27 pounds per square foot for machines having a maximum horizontal speed of 100 miles per hour, 38 pounds per square foot where the maximum horizontal speed was 120 miles per hour, and so on for higher or lower speeds, the load per unit of area varying as the square of the speed. For machines making 100 miles per hour this corresponded to a tail load of 5.4 pounds per square foot for each unit of dynamic load. This is very nearly equal to the relation between these two loads now laid down in the Air Service's specifications for fuselage sand load tests, where it is prescribed that the tail load shall be 5 pounds per square foot for each unit of dynamic load. A fuselage should, with this type of loading, stand a dynamic load of at least 4, with 20 pounds per square foot on the tail. The general specifications of the Bureau of Construction and Repair, United States Navy, fix the required tail load at 20 pounds per square foot, but combine with this only the weight of the machine without a dynamic factor.

These specifications relate primarily to flying loads. In studying the distribution of load on landing, also, there is some difference of opinion as to the best method of procedure, although the vexed question of tail loading is avoided in this case. Obviously there are many different ways in which a landing may be effected, and the distribution of the landing loads, as well as their magnitude, will vary with the speed of the machine, its attitude at the instant of touching the ground, the position of the controls, the nature of the ground, and a number of other factors.

The method adopted in this report is, in the main, the straightforward one of choosing a standard type of machine, analyzing it by many different methods, and comparing the results. The loadings for all of the seven cases studied are illustrated in figures 1 and 2, and the stresses in the members for all the loadings tried are tabulated at the end of the report.

In the tabulation, the largest stress occurring in each member has been printed in italics. Where the same member may take tension or compression under different loadings, the maximum stress of each sort is printed in italics. In picking out the maxima, Case VII was ignored for reasons which will be apparent later. In some cases it has been possible to make results clearer by analytical discussion, but the graphical analysis has been carried through in every case. The dynamic factor used is 5 in all cases, this being considered to allow for very heavy landings and also for the worst loads experienced in flying. If the sizes of members were being selected, a further "material factor" or true factor of safety of about 1½ should be allowed over the tabulated stresses (i. e., the ultimate strength of each member should be at least 1½ times the largest stress set down against that member in the table).

If a really thorough and accurate analysis of the stresses in an airplane were to be made it would be necessary to treat the whole structure as a unit instead of separating wings and

fuselage as is the invariable custom. The drag wires and other members so inter-connect the parts of the machine that no single part can be treated independently with strict accuracy. So many uncertainties arise, however, chiefly due to the presence of redundant members, the stress in which is determined by the rigidity of their end connections and by the initial tension with which they are set up, that it is usually best to consider these redundant inter-connecting members as additional safeguards, and not to take them into consideration in figuring stresses. There are some conditions, however, as will be seen in connection with Case VI, where it would be manifestly absurd to ignore entirely the effect of the external drag wires on the fuselage stresses.

The fuselage adopted is similar to that of the JN4H. The layout of the center lines of the members is identical with that in the JN4H, but the load distribution differs in some particulars from that adopted in the Curtiss design, and the stresses given in the report therefore should not be taken as representing those actually existing in the JN.

LANDING LOADS.

The landing stresses have been examined on four different sets of assumptions, three relating to landings with the tail high, the fourth to those with the tail low (three-point). The lift of the wings has been neglected in all cases. Its inclusion or omission has little effect on any stresses except those in the chassis struts and in the vertical members directly over them. If the weight of the airplane be broken up into loads applied at the panel points in the usual manner, and if the sum of these loads be opposed by a vertical force acting at the axle, which is manifestly the only place that it can act until the tail skid touches the ground, the resultant of the loads at the panel points will pass through the center of gravity, while the vertical through the axle will pass well forward of this point. Therefore, although the two resultant forces are equal in magnitude and opposite in direction they are not directly opposed, and their resultant is a turning moment which, if a landing were actually made under these conditions, would whip the tail of the machine violently downward. Actually, however, the force applied at the axle is not vertical, but is inclined backwards by the frictional resistance to forward motion. This frictional resistance varies widely with the nature of the ground, but it is common to arbitrarily assume, in order to simplify the analysis, that it is just sufficient to incline the line representing the resultant ground reaction until it passes through the center of gravity. If this assumption be made the two resultant forces (ground reactions and resultant of loads at panel points) no longer give a moment, as they both pass through the center of gravity, but they are no longer directly opposed, and there is an unbalanced horizontal force which must be taken care of in order that complete statical equilibrium of the structure may be secured. The securing of statical equilibrium is, of course, an essential condition for the closure of any stress diagram. The horizontal component of the ground reaction has been treated in two different ways (Cases I and III). In the first, it is assumed that this force is not balanced by any external force, and that the machine is therefore decelerating. The deceleration of the several weights applied at the panel points tends to throw them forward, and the resultant of the weight and the inertia force lies in a line parallel to the resultant ground reaction. Since the vertical component of each force remains unchanged, the load at each panel point should be multiplied by the secant of the angle through which its line of action is turned by the inertia force. This method of applying landing loads was first suggested and applied by J. A. Roché.[1] The distribution between the upper and lower panel points of the parts of a load is inversely proportional to the distances from the load to the panel points (just like the supporting reactions for a simple beam). This is rigorously correct for the horizontal components, but not for the vertical ones, since the end fixtures of fuselage struts usually will not transmit tension, and vertical loads applied between the ends of the strut are transmitted to the longeron entirely at the lower end of the strut. It was shown in Mr. Roché's article that the maximum stresses are not changed in any member if the vertical and horizontal loads are both divided between the upper and

[1]Methods Used in Finding Fuselage Stresses ,by J. A. Roché: Aerial Age, July 23, 1917, vol. 5, p. 642.

lower panel points in the proportion correct for the horizontal ones, and such an arrangement of loads, making the lines of action of all the forces parallel to each other, greatly simplifies the work. The second method is to balance the horizontal component of ground reaction directly by a thrust load. This is the condition in taxi-ing, and is illustrated in Case III. The assumption that the thrust is large enough to balance completely the horizontal component while the dynamic load is a maximum is rather severe, as the thrust would have to be about equal to the weight of the machine when the dynamic load was 5. The figures obtained on this assumption, however, at least serve to show in which members the stress is increased by a thrust load.

Case II is intended to relate to the same condition as Case I, but in a simplified form making it unnecessary to deal with inclined loads. Instead of taking the reactions at the points of attachment of the chassis strust as passing along the struts, so that their resultant might pass through the axle, the resultant of the panel-point loads is opposed, in Case II, by a vertical force passing through the center of gravity. The forces in the chassis struts are then arbitrarily replaced by two vertical forces acting at the same points and so proportioned that their resultant is the line just spoken of. All external forces are then vertical, there are no inertia forces, and the resultants of the upward and downward forces both pass through the center of gravity and there is complete equilibrium. This is manifestly an easy case to deal with, and the stress diagram in Case II is much simpler than that in Case I, where the external forces can not all be represented on a single straight line. The simplified method has been used by the airplane engineering department of the Air Service.

It is evident that the entire omission of the horizontal components of the chassis strut forces will have a considerable effect on the stresses in the longerons in the bays between the points of attachment of the two struts. This is particularly noticeable in a machine like the JN, where the upper ends of the chassis struts are widely separated and their slope is small. An inspection of the tabulation of the results of the analyses shows that the stresses in the top longeron near the rear of the body are greater for Case II, those in the bottom longeron for Case I. This is natural, as the inertia components of the loads, acting from the free end toward the supporting reactions, tend to increase the compression in the lower longeron and counterbalance the tension in the upper one. The stresses in the struts and wires are nearly the same for the two cases except in the bays between the points of attachment of the chassis struts. This, again, is what might be expected, as, the longerons being nearly parallel and horizontal, the primary duty of the wires is to carry the shear due to vertical loads, while the strut compressions are almost exactly equal to the vertical components of the stresses in the adjacent wires. Strut and wire stresses are therefore substantially unaffected by horizontal components of load at the panel points. In no case, except in the bays between the chassis struts and in a few other bays of the top longeron, is the difference of stress in a member for the two cases as much as 5 per cent. The percentage difference is large in some of these cases, but only where the magnitude of the stresses is small and where the factor of safety would be sure to be very large. The simplified method of Case II leads to an overestimation of the top longeron stresses, as compared with Case I, by about 100 pounds in one bay. The important differences come in the bays between chassis struts. The type of loading used in Case II is manifestly wrong for these bays, and the inclusion of the horizontal components of the strut reactions changes the magnitude of the stresses very radically. In the case of the lower longeron, the effect of these components is to change the stress from a large compression to a tension. The difference between the two cases in the upper longeron is much smaller but the simplified method is not on the safe side. In the struts, the stress given by the simplified method is too high in the member directly over the rear chassis strut, and too low in all others. The only pair of wires much affected is that in the rear bay, where different wires are in tension in the two cases.

Summing up, it is evident that the method of Case II is satisfactory for the rear of the body, but that it gives results very badly in error for some of the members in the neighborhood of the chassis attachment. The simplified loading can well be used for a preliminary analysis to assist in estimating the sizes of members, but it should not be considered as satisfactorily covering the landing loads by itself. When it is employed there should be added to the stresses in the

bays of the lower longeron between the chassis struts an amount equal to the horizontal component which would exist in the adjacent chassis strut if the loading of Case I were used. This horizontal component can be found by drawing a triangle of forces. (The addition is algebraic, compressions being taken as negative, and the effect usually is to change the sign of the stresses.)

Case III (ground friction balanced by thrust) gives results identical with those of Case II for all members behind the rear chassis strut. The effect of thrust can be satisfactorily allowed for by adding (algebraically) one-sixth of the weight of the machine to the stress in every bay of each longeron from the nose to the front chassis strut, and one-tenth the weight to the stresses in the longerons between the chassis struts. If the engine is carried in such a way that the thrust can only be transmitted to the fuselage at the rear of the bearers the addition to allow for thrust load can, of course, be omitted forward of this point.

Case IV relates to a three-point landing. The largest dynamic loads usually occur in this type of landing, as a pilot having a forced landing on rough ground will land at as low a speed as possible, and the tail-skid will therefore come into contact with the ground before the shock absorbers on the wheels have had time to extend fully. The only case in which a large dynamic load is likely to occur on a high-speed landing (I and II) is that in which the pilot is unskilled or landing in the dark and fails to flatten out early enough. In considering the landing with tail low all the loads have been taken perpendicular to the top longeron. The effect of friction and of inertia loads is thus allowed for, as the perpendicular to the top longeron makes an angle of about 10° with the true vertical when the machine is resting on the ground. To be strictly accurate, the reactions should be drawn with different inclinations, as the coefficient of friction of the tail-skid is much greater than that of the wheels, but the effect of allowing for this difference would be too small to warrant the additional complication. Since the point of contact of the tail-skid is some distance behind its point of attachment, the reaction of the tail-skid has a moment about its hinge. This is allowed for in the way in which it is actually taken through the hinge and shock-absorber cord in the machine, by putting on equal and opposite horizontal forces at the top and bottom of the strut where the tail-skid is attached. Since the pull in the shock-absorber cord has a vertical component, there should be added another pair of vertical forces, equal and opposite. These have been omitted from the diagram, as their only effect is to increase the compression in the strut over the tail-skid.

The tail-skid load reverses the stresses in the longerons behind the rear chassis strut and changes the diagonal which takes tension in several cases, as compared with the loading arrangements which have already been considered. The stress in the front chassis strut and in the fuselage strut directly opposed to it are also somewhat greater in a three-point than in a two-point landing, because of the backward inclination of the reaction causing the front strut to carry a smaller share of the total load in the latter case than in the former.

The conclusion is that landing stresses should be analyzed for three-point landings (Case IV) and for two-point landings with inclined ground reaction and inertia loads (Case I) and that allowance should be made for the effect of thrust on the stresses in the forward bays of the longerons, especially the upper one. If only one stress diagram is to be drawn for landing loads it should be for the case with tail-skid reaction, as the analysis for flying conditions is very similar in most particulars to that for a two-point landing, and gives stresses of the same order in the rear of the body, whereas there is no other type of loading which resembles that encountered when landing with tail down closely enough to be substituted for it.

FLYING LOADS.

It is customary, in analyzing the fuselage stresses under flying conditions, to consider only the rear portion of the structure, and to treat this as a cantilever loaded in accordance with some set of assumptions and supported either at the rear wing spars or the lower spars. The first assumption as to the support is the more common, but the United States Navy specifications call for an analysis with the reactions taken at the lower wing hinges, which appears to be more logical.

It is very desirable that the analysis under flying conditions be extended to cover the whole structure, from nose to tail. While this is not possible by an extension of the ordinary method with an arbitrarily fixed tail load, the stress diagram failing to close if it is carried on past the wing hinges to the nose of the airplane, a closed diagram can always be secured if full account is taken of all the forces acting on the airplane and of its motions under those forces.

The downward loads on an airplane fuselage in flight may be divided into dynamic loads and tail loads. The dynamic loads are due to the acceleration of the center of gravity of the machine (usually an acceleration parallel to the normal axis of the machine, arising in flattening out after a dive or in some similar sudden change of course). Since the lines of action of the dynamic loads on all parts of the machine at a given instant are parallel so long as there is no angular acceleration of the airplane about its C. G., and since the dynamic loads at the panel points are proportional to the weights concentrated at those panel points the resultant of these loads always passes through the C. G. of the machine.

The tail load, in turn, may be divided into three parts. First is the load, usually downward, required to give static equilibrium about the C. G. This part of the load usually has, for any particular machine, a maximum value of about 4 per cent of the wing loading, its exact magnitude depending on the position of the center of pressure of the wings with relation to the center of gravity. For tail surfaces of normal size, this gives a unit loading of about one-quarter of the unit wing loading. The second part of the tail load goes to overcome the damping moment (M_q) due to the body, wings, and chassis. This moment is about 18 per cent of the total damping moment due to the action of the air against the pitching airplane.[1] The manner of its distribution is uncertain, and in these illustrative examples it was arbitrarily distributed among the various panel points in such a way that the applied forces would sum up to zero, that the sum of their moments about the C. G. would be equal to 18 per cent of the computed total damping moment, and that the loads would be approximately proportional to the distances of their points of application from the C. G. The tail load due to damping appears only when the airplane is rotating about its C. G. (with respect to axes fixed relative to the earth). Finally, there may be an excess of tail load above the sum of these two components, and this excess acts to impart an angular acceleration to the airplane.

In considering tail load, the component of damping due to the tail (82 per cent of the total) must be subtracted from the apparent load to get the true value of the total force acting. The total tail load in any machine at a given instant is then a function of elevator setting, angle of attack, speed, and angular velocity.

It was just demonstrated that two of the three portions of the tail load can be so balanced as to give static equilibrium, the first by the wing load acting at a certain distance from the center of gravity, the second by properly distributed damping loads at the panel points. To balance the third component, the excess producing angular acceleration, inertia loads must be applied much as in the case of the deceleration when landing, the difference being that in this case the structure is treated for the moment as though it had no motions except one of rotation about the C. G., and the inertia load at each panel point therefore acts perpendicular to the line connecting that panel point with the C. G. The ratio of the inertia load to the static load at any panel point is directly proportional to the distance from the C. G. Since the dynamic loads and each component of the tail load taken separately can be balanced by properly allowing for the accelerations, it is evident that any combination of loads can be so balanced, and that it is possible to draw, for any set of fuselage loads which can occur, a closed stress diagram taking in every member of the fuselage and with the wing reactions applied as they actually are in practice.

The dynamic loads can only attain their maximum value when the angle of attack is large, and it therefore requires a perceptible interval, after the elevator is pulled up to flatten out from a dive, for the lift on the wings to reach its highest point. The total down load on the tail, on the other hand, reaches its maximum instantly, as the down load is largest when the

[1] *Third Annual Report of the National Advisory Committee for Aeronautics*, p. 335: Washington, 1918.

angle of attack is small, when the speed is high, and when the angular velocity and damping moment are small, and all of these conditions are best fulfilled when the airplane is diving and the elevator has just been pulled up. It is then evident that the tail loads and dynamic loads can not reach their maxima at the same time, and any analysis based on the assumption of large loads of both types simultaneously applied is unduly severe.

Furthermore, any analysis in which a maximum down load is applied on the tail and balanced only by reactions at the wing hinges is unduly severe. When there is a large tail load there always exists an angular acceleration, and this produces inertia loads which act upwardly on the rear part of the body, directly balancing the tail load. It can not be too strongly emphasized that the structure as a whole will always be in statical equilibrium if the inertia and damping loads are properly applied, and that there is something wrong with any set of loading assumptions which permits of the existence of an unbalanced moment about the center of gravity.

In connection with the present report the typical fuselage has been analyzed for three different types of flying loads. Cases V and VI were carried through in accordance with the methods just discussed, all inertia loads being included. Case V relates to the maximum dynamic load, Case VI to the maximum tail load. In Case VII an analysis was made for the rear position of the body in accordance with the common assumptions of a dynamic factor of 5, a tail load of 25 pounds per square foot, and the rear of the body acting as a cantilever supported at the rear wing spars.

The fundamental data for Cases V and VI were based on an analysis of the behavior of a JN in a dive and loop, an analysis the most important results of which were published in the Bulletin of the Airplane Engineering Department, United States Army. In connection with the discussion there printed the effect of inertia loads arising from angular acceleration was taken up, but no attempt was made to carry through a complete analysis of the stresses under flying conditions. The assumptions on which that analysis was based were rather too severe, as the maximum dynamic factor by computation was 8.14, whereas it has been shown by accelerometer tests that the dynamic factor seldom rises above 4 and apparently never reaches 4.5. A dynamic factor of 5 was taken as the standard in these illustrative problems, just as for the landing loads, and the computed lifts, tail loads, accelerations, etc., were therefore reduced in the ratio $\frac{5.00}{8.14}$. This procedure is not entirely justifiable, but it gives as good results as can be attained without another complete analysis of a dive.

Case V relates, not to the exact instant of maximum dynamic load, but to the time, 0.42 second after pulling up the elevator, and 0.1 second before the peak of the dynamic load curve is reached, when the angular acceleration is zero. This very much simplifies the analysis by eliminating the "rotative inertia" loads in this case, and has little effect on the total stresses, as the dynamic load at the instant when the angular acceleration disappears is only 4 per cent below its maximum value. The angle of attack of the wings, in this case, was about 12°, and the resultant force on the wings was therefore very nearly perpendicular to the chord. The total lift was divided among the four wing hinges on each side, the lower hinges taking about 85 per cent. of the total lift because of the transmission of lift from the upper wing through the inner lift cables to the lower hinges. The distribution between the front and rear hinges depends on the position of the center of pressure. The tail load vector was arbitrarily drawn parallel to that for wing load, although the L/D for the tail is less than that for the wings. The stresses in the fuselage would be very little affected by changing the slope of the tail vector.

The normal tail load for the speed, angle of attack and elevator angle existing at the instant to which Case V relates would be 10 pounds per square foot if there were no angular velocity. The attribution of 82 per cent of the damping moment to the tail and the deduction of the appropriate amount from the tail load reduces this by about 70 per cent, so that the actual tail load corresponding to a dynamic factor of 5 is 2.5 pounds per square foot. This figure would be larger in a machine where the center of gravity was farther forward relative to the wings, but it would never exceed 10 pounds per square foot. No attempt was made to

distribute the drag of the body, the whole amount being combined with the wing drag and applied at the hinges. There, again, the procedure is not rigorously correct, as most of the fuselage drag should act at the nose, but the difference between the exact and approximate distribution of fuselage drag would be negligible.

Thrust and torque loads do not appear in any of the analyses under flying loads, as the speed in a limiting dive is so high that there could not be any thrust or very much torque, the propeller tending to operate as a windmill rather than as a propeller. The thrust and torque loads appear in normal flight, and may be important enough to require special analysis in high-powered airplanes with engines having a very low weight per horsepower. There is a gyroscopic torque when flattening out from a dive, and this modifies the stresses in the fuselage members lying in horizontal planes, including the longerons, but it will not be considered in this report.

The analysis in Case VI is very complex, as the loads act in every conceivable direction. They divide, in general, into three groups. First are a set of loads due to translational accelerations. These all act along parallel lines, and, since the lift at the instant after the elevator is pulled up is insignificant, their lines of action are very nearly parallel to the flight path, the only acceleration which amounts to anything being the negative acceleration along the path, due to the excess of total drag over the component of gravity along the path. The second group is made up of the inertia loads due to angular accelerations. Since the lines of action of these loads are perpendicular to the lines connecting their respective panel points with the center of gravity, no two of them act in the same direction, and the drawing of a load diagram becomes a rather complicated and tedious operation. Lastly, there are the external loads, due to air pressure, which balance all these inertia loads. The total load on the tail is roughly 31 pounds per square foot, and its component perpendicular to the flight path is approximately equal to the corresponding component of the force on the wings, so that the resultant is, as already noted, parallel to the flight path. The vector of force on the wings at the very small angle of attack existing during the dive ($-3\frac{1}{2}°$ for this particular machine) is inclined at about 45° to the perpendicular to the chord, and there is therefore a large component of this force which must be taken by the drag bracing. This bracing system has several redundancies, as there are three external drag wires on each side of the fuselage, and there is also a possibility that the drag may be carried through the stagger wires to the lower wing and thence directly to the fuselage at the lower wing hinges. The distribution of the drag between these four alternative routes is necessarily uncertain, depending largely on the initial tension in the several members, but it is absolutely certain that a large share of the drag is transmitted through the external bracing to the nose of the fuselage in a machine which, like the JN, has no stagger wires in the center section. In Case VI it was assumed that 90 per cent of the drag was taken through the external bracing and 10 per cent at the wing hinges, and that the drag taken by the external bracing was divided equally between the upper and lower wires. From the structural standpoint it is desirable to take as much drag as possible through the upper drag wires, as these wires also carry some lift directly to the nose of the fuselage, greatly reducing the stresses in the forward portion and also reducing the stresses in the inner bay of the wing truss.

There is no damping load to be deducted from the tail load in Case VI, as the machine can not acquire an angular velocity instantaneously when the tail is pulled up.

A comparison of the stresses in Cases VI and VII shows that the ordinary method, neglecting all inertia loads, gives stresses far higher than those which can actually prevail, the overestimation in some cases being as much as 200 per cent.

Examination of the tabulated stresses for the first six cases shows that the maximum stress in most instances occurs in Case IV, V, or VI. The maximum comes in Case I in a few instances, but the stress in Case I never exceeds by more than 20 per cent the maximum among IV, V, or VI. As already noted, a dynamic load factor of 5 in a tail-high landing would be a very rare occurrence. Case III also shows a few maxima, but only in the forward three bays, and these bays can be taken care of by adding in a correction for thrust in the manner explained in the first part of this paper. Cases IV, V, and VI, then, may be considered as furnishing a

complete and satisfactory analysis. Furthermore, since the maximum stresses occur in Case VI only in the three rear bays of the fuselage it is sufficient, if the work is to be reduced to a minimum, to start the stress diagram for the condition of maximum tail load at the tail post and carry it through the three or four rearmost bays.

Since the complete analysis of a dive has been carried through for only one machine, it is necessary to make certain assumptions as to the magnitude of the damping moments in order to determine the load distribution analogous to Case V for a new machine. The angle of attack for a dynamic load factor of 5 may be taken as 12°, and the tail load required to balance the moment of the wing load about the C. G. can then be computed. Two pounds per square foot, of tail surface should be added to this to allow for damping, and static equilibrium restored by modifying the dynamic loads in the manner already described.

Cases analogous to VI require fewer assumptions, as there is no damping. The total tail load can be determined from a wind tunnel test of a model with the elevators turned up or approximated from the results of such a test on a similar machine. The tail load required to balance the wing moment can be computed as before, the angle of attack being computed for a 45° dive at limiting speed. All the rest of the tail load goes to produce angular acceleration, and is balanced by inertia loads applied in the manner already described. The distribution of the drag will differ in different types of machines, and no definite rules can be laid down, but caution should be exercised not to make the pull in the upper drag wires too large, as the apparent stresses are reduced by so doing. It is better to keep on the safe side and take an excessive proportion of the drag in the lower wires and at the wing hinges.

These notes on loading also furnish some suggestions for the making of sand load tests on fuselages. It is evident that a load of 20 pounds per square foot on the tail, whether or not it is accompanied by a dynamic load, produces larger stresses than would be experienced in practice, and a sand load for maximum tail load would correspond more nearly to actual conditions if upward loads were applied by ropes passing over pulleys and attached at the panel points, to represent the effect of "rotative inertia." If a single sand load test is to be made, however, it would be better to have the loading correspond to the conditions of Case V, with some increase in the tail load to bring the stresses in the rear bays nearer to the maxima found in Case VI. The specifications would then be:

Tail load of 12 pounds per square foot corresponding to a dynamic load of 5, these loads being increased in the same proportion until failure. (These loads are for a training machine. For airplanes having a normal wing loading of over 6 pounds per square foot, the tail load corresponding to a dynamic factor of 5 should be increased, reaching a maximum of 18 pounds per square foot when the normal wing loading is 10 pounds per square foot.)

The loads at panel points not to be exactly equal to the product of the dynamic factor by the weight concentrated at the panel point, but to be increased forward of the center of gravity and reduced behind the C. G. to allow for damping effect on the body and appendages (not including the tail unit). The percentage of increase or reduction should be proportional to the horizontal distance from the C. G. to the point of application of the load, and the total moment about the C. G. of these changes of load should be such that, when the fuselage is supported at the lower wing hinges, the supporting reactions will be in inverse proportion to the distances from the hinges to the center of pressure of the wings at an angle of attack of 12°. This will do away with the difficulty now experienced when a large tail load is applied in a sand load test without any allowance for damping or inertia loads. The fuselage tends to pivot about the rear support, and it is necessary arbitrarily to add a large concentrated load at the extreme nose in order to prevent local failure at the rear support.

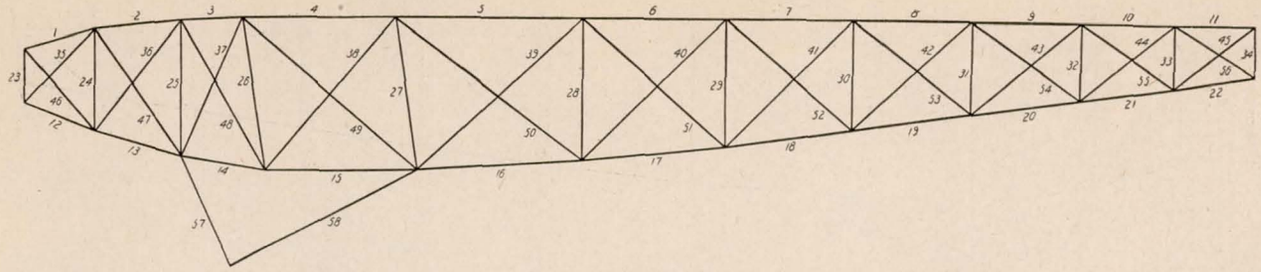
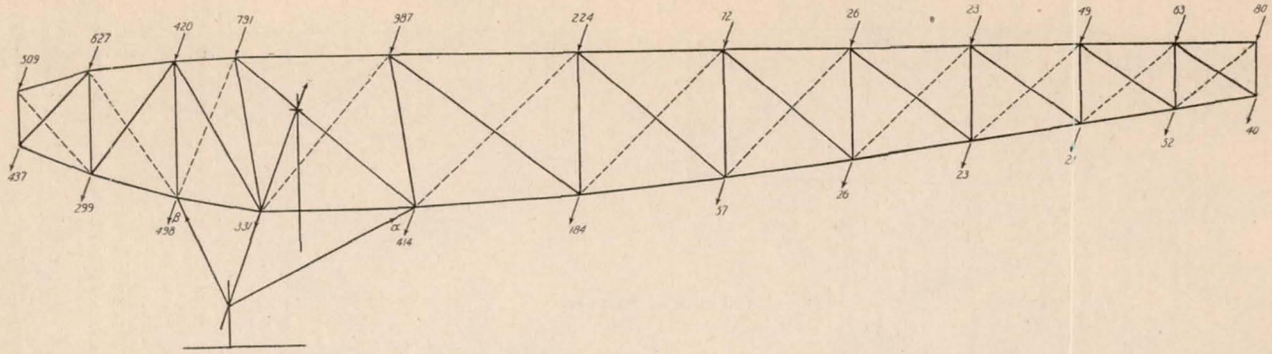
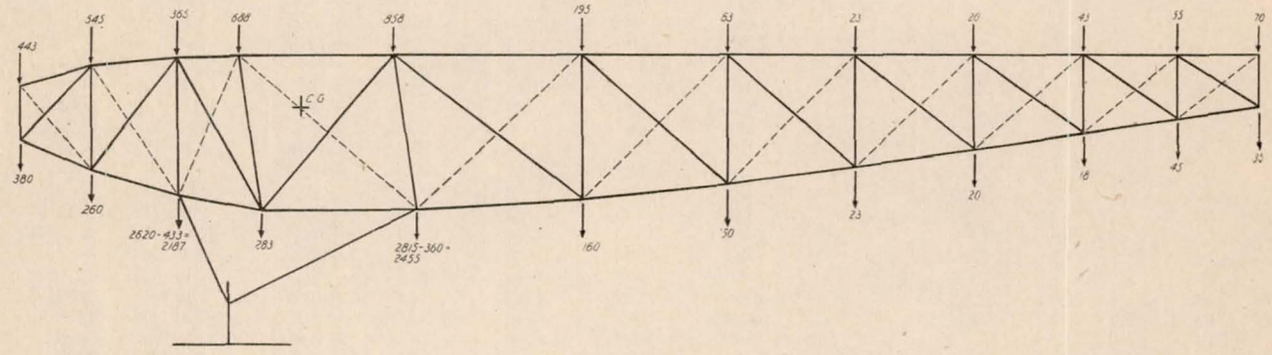


Table of Stresses.

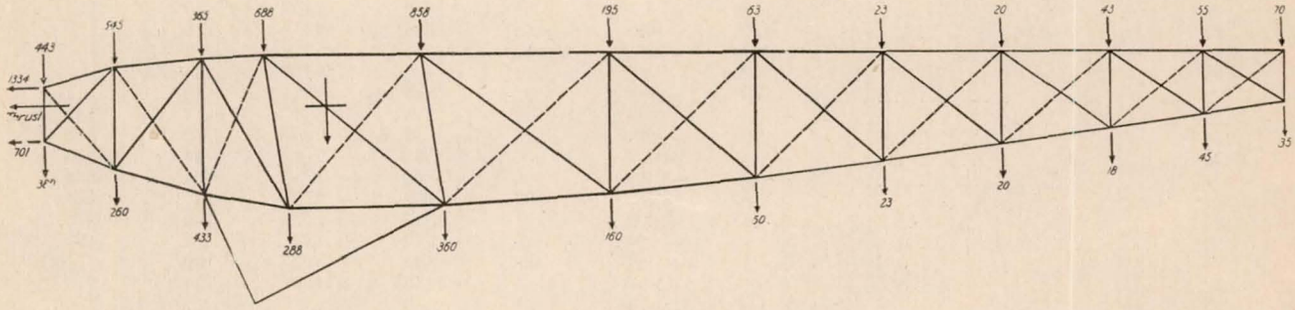
Number.	Case I.	Case II.	Case III.	Case IV.	Case V.	Case VI.	Case VII.
1	+ 200	0	*+1392*	0	+ 17	− *92*	.....
2	+1114	+ 580	*+1810*	+ 580	+ 590	+ 44	.....
3	+1466	+1195	*+2200*	+ 505	+1553	+ 206	.....
4	+1797	+1305	+2123	− *712*	*+2194*	+ 431	.....
5	+1120	+1435	+1435	− *425*	*+1519*	+ 757	+4330
6	+1070	+1074	+1074	− *523*	*+1189*	+ 792	+3620
7	+ 837	+ 839	+ 839	− *533*	+ *946*	+ 763	+3063
8	+ 591	+ 606	+ 606	− *533*	+ *709*	+ 707	+2470
9	+ 321	+ 358	+ 358	− *488*	+ 446	+ *606*	+1745
10	+ 94	+ 133	+ 133	− *188*	+ 189	+ *429*	+ 918
11	− *29*	0	0	0	+ 5	+ *89*	0
12	− 549	− 625	+ *223*	− 625	− *661*	− 209	.....
13	−*1540*	−1513	− 774	−1513	−1531	− 313	.....
14	+ 524	−1500	+ *886*	+ 448	−*2375*	− 400	.....
15	+1177	−1980	+*1395*	+1133	−*2841*	− 680	.....
16	−*2766*	−2343	−2343	− 98	−2430	− 760	−5793
17	−*1683*	−1540	−1540	+ *425*	−1553	− 760	−4355
18	−*1260*	−1086	−1086	+ *528*	−1191	− 746	−3650
19	− *991*	− 849	− 849	+ *493*	− 968	− 709	−3098
20	− 714	− 611	− 611	+ *389*	− *728*	− 648	−2498
21	− 431	− 361	− 364	+ *148*	− *462*	− 543	−1768
22	− 166	− 134	− 134	− 134	− 199	− *355*	− 928
23	− 457	− 450	− 55	− 450	− 447	− *470*	.....
24	−1260	−1088	−*1268*	−1088	−*1093*	− 121	.....
25	−3089	−2043	−2740	−*3200*	−1564	− 182	.....
26	−1089	− 490	− 944	−1430	−*2587*	− 265	.....
27	−1786	−*2363*	−1573	−1278	−1064	− 136	.....
28	− *586*	− 511	− 511	− 283	− 503	+ *3*	− 843
29	− *309*	− 273	− 273	− 43	− 260	− 12	− 550
30	− *237*	− 206	− 206	− 23	− 212	− 38	− 495
31	− *220*	− 196	− 196	− 60	− 205	− 64	− 533
32	− *220*	− 194	− 194	− 138	− 215	− 100	− 608
33	− 160	− 141	− 141	− *333*	− 177	− 180	−6438
34	− 77	− 70	− 70	− 70	− 122	− *294*	− 695
35	+ *954*	+ 820	+ 468	+ 820	+ 827	+ 100	.....
36	+*1717*	+1456	+1555	+1456	+1492	+ 194	.....
37	0	0	0	0	+*1188*	+ 252	.....
38	0	+*1045*	0	0	0	+ 337	.....
39	0	0	0	0	0	+ *86*	.....
40	0	0	0	0	0	0	.....
41	0	0	0	0	0	0	.....
42	0	0	0	+ *58*	0	0	.....
43	0	0	0	+ *145*	0	0	.....
44	0	0	0	+ *293*	0	0	.....
45	0	0	0	0	0	0	.....
46	0	0	0	0	0	0	.....
47	0	0	0	0	0	0	.....
48	+ 529	+ 585	+1195	+*1860*	0	0	.....
49	+ 377	+ 0	+ 288	+*1065*	+ 790	0	.....
50	+*1283*	+1134	+1134	+ 655	+1109	0	+1825
51	+ *543*	+ 475	+ 475	+ 130	+ 478	+ 19	+ 950
52	+ *360*	+ 319	+ 319	+ 8	+ 301	+ 45	+ 740
53	+ *337*	+ 300	+ 300	0	+ 305	+ 75	+ 758
54	+ *337*	+ 303	+ 303	0	+ 324	+ 127	+ 893
55	+ 297	+ 273	+ 273	0	+ *311*	+ 220	+1003
56	+ 171	+ 158	+ 158	+ 163	+ 234	+ *408*	+1093
57	−4489	Ind.	−3900	−*4545*	.....	.....	.....
58	−*4629*	Ind.	−4105	−2070	.....	.....	.....



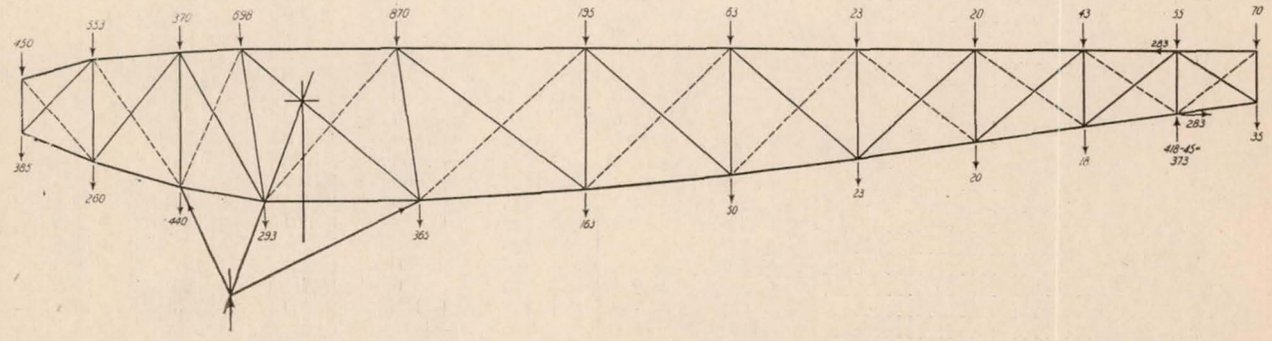
Case I.



Case II.

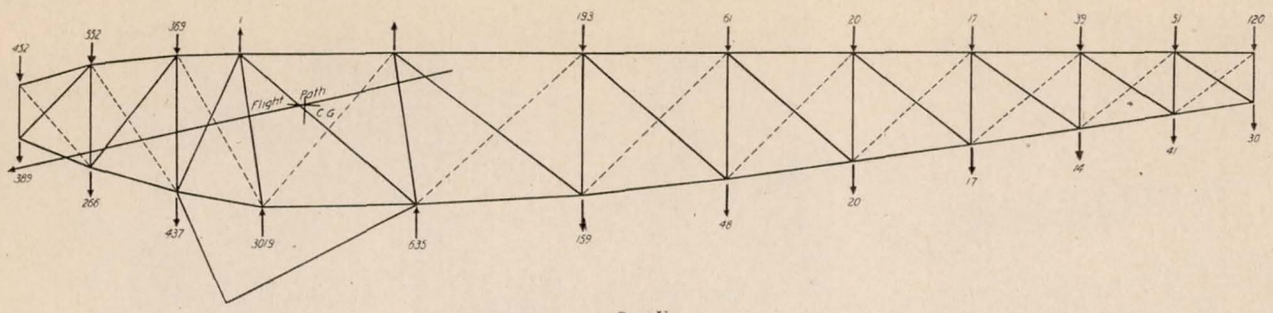


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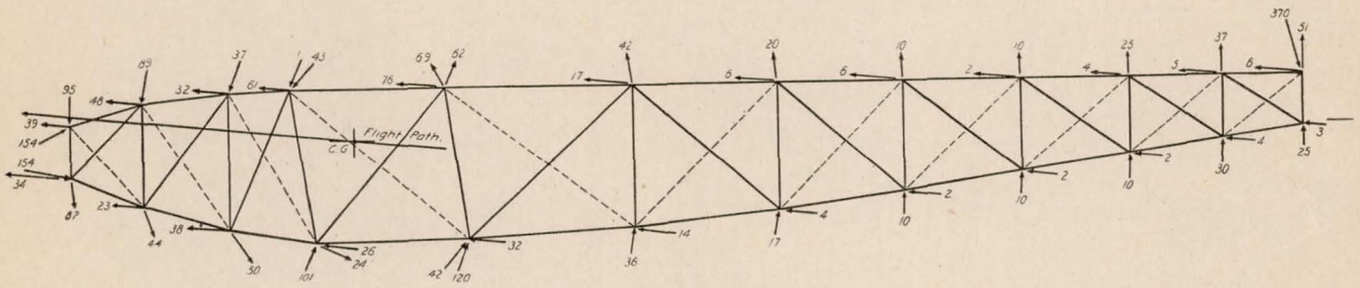


Case IV.

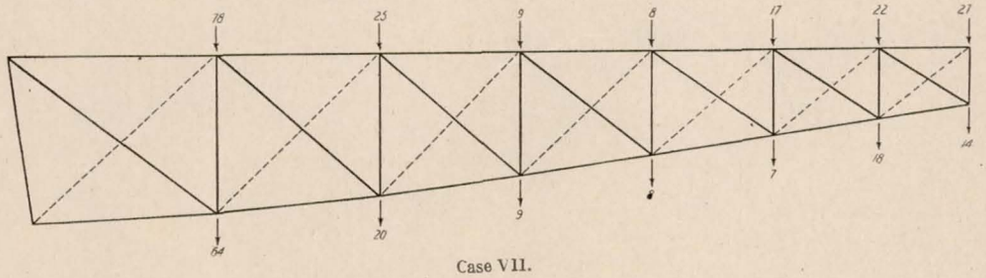
FIGURE 1.



Case V.



Case VI.



Case VII.

FIGURE 2.

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REPORT No. 77

THE PARKER VARIABLE CAMBER WING

BY H. F. PARKER.

Bureau of Standards, Washington, D. C.

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REPORT No. 77.

THE PARKER VARIABLE CAMBER WING.[1]

By H. F. Parker.

[Introduction—Rib structure—Rib tests; Conditions of test; Results of tests—Aerodynamical tests—Discussion of Wind tunnel results; Monoplanes biplanes; triplanes—Summary.]

INTRODUCTION.

The most important single problem in aeronautics awaiting solution is that of increasing the speed range of airplanes. In recent years maximum speeds have been increased very greatly, and will no doubt be still further increased, but each addition has been accompanied by an increase in the landing speed. The landing speed has always been about half the maximum and could not be reduced below that amount without entailing the expenditure of additional power. This is due primarily to the properties of the type of wing which has been used.

In flying, the method utilized to change the speed is to alter the angle of attack of the planes. This must also be accompanied by an alteration in the power output of the engine if the machine is to be kept flying level. Manipulation of the engine throttle without alteration of the angle of the planes will not cause a change in speed; the machine will ascend or decend at its former speed. The speed is therefore dependent on the angle of attack. If this could be efficiently varied from a very small to a very large angle, a wide range of speeds could be obtained. Two things prevent this: First, the lift does not increase directly with the angle of incidence for all angles. It does do so up to about 15° but for greater angles, instead of increasing, the lift actually falls off. This falling off occurs in all types of wings though in some cases it is only slight and in others very considerable. It is well shown in the lift curves in figure 14, and is also apparent in all the other lift curves shown in this report—in figures 8, 17, and 20. Consequently no increase in speed range can be obtained by increasing the angle of incidence beyond 15°. Second, the efficiency of the plane is not maintained at low angles. As the incidence is reduced from the maximum of 15°, both the lift and the drag decrease, the drag at first falling off more rapidly than the lift. At about 3° a point is reached where the ratio of lift to drag is a maximum. This is the most efficient flying angle for the plane. As the incidence is further decreased, the lift continues to fall off rapidly. The drag, however, decreases more slowly, being a minimum at zero incidence. For negative angles it again increases.

This means that the ratio of lift to drag falls off very rapidly, and the wings of a machine flying at a smaller angle of incidence than 3° offer more resistance than they do at that angle. The line from which these angles are measured is the chord of the aerofoil, i. e., the common tangent to the lower surface. It will be noticed that this is not necessarily the position in which the wing gives no lift. Most wings give a considerable lift when their chord line is parallel to the direction of the air flow, and this lift only becomes zero when the nose of the wing is about 3° below the trailing edge. In fact, fast machines frequently fly with their planes set at negative angles.

If a maximum speed of double the minimum is to be obtained, the machine must fly under the inefficient conditions existing at these small positive or even small negative angles of incidence. If it is to be more than double, as it must be in order to obtain a reasonable landing

[1] At the time this wing was designed it was Mr. Parker's belief that the wing would be automatic in operation. Subsequent examination indicates that this is not true, at least for the rib as now designed. Means for flexing the wing mechanically are not discussed.—*Ed.*

speed in machines flying at over 100 miles an hour, the small lift necessary at high speeds is accompanied by a prohibitive drag.

The problem of increasing the speed range may be approached in a number of ways, but confining ourselves to devices applicable to the present type of airplane, which eliminates the helicopter and similar machines, there are three ways by which a solution might be achieved. These are:

Variable angle of incidence.
Variable surface.
Variable camber.

Each of these presents great mechanical difficulties, but the first is the easiest of attack and has consequently approached nearer a solution than either of the other two. It offers two advantages: First, the axis of the fuselage can be kept parallel to the path of flight at all speeds, thus securing a minimum drag over the entire speed range. In the present machine, having the wings fixed in relation to the fuselage, the fuselage is at a considerable angle to the flight path over a portion of the speed range. Under these conditions the variable incidence machine is more efficient than the present type. Over that portion of the speed range where the fuselage of the standard machine lies along the flight path, or only a few degrees from it, the variable incidence machine offers little or no advantage. Second, the wings of the variable incidence machine can be tilted to a much greater angle than is possible in the present machine. This permits the machine to be brought to rest more rapidly. It does not, however, reduce its minimum flying speed. Thus the advantages of variable incidence, though well worth attainment, do not provide a sufficiently complete solution of the problem.

The next for consideration is variable surface. Theoretically, this gives a perfect solution. If the wings of the airplane could be increased in area during flight, the speed could be reduced so as to land as slowly as desired. Conversely, given sufficient surface to insure a low enough landing speed, if the surface could be reduced in flight the planes could always be made to operate at the angle of incidence giving the best lift/drag ratio, thus securing the least possible drag at maximum speeds. Unfortunately, mechanical difficulties prevent the realization of this method. These difficulties are so serious that there does not seem any prospect of their being overcome in the near future.

Finally, there is variable camber. This offers advantages very much greater than variable incidence, but is more difficult of solution mechanically. On the other hand, as compared with variable surface, it is mechanically possible, but its aerodynamic advantages are not quite so great. Yet they are, however, great enough to provide a satisfactory solution of the problem and the only one, apparently, which is practicable.

So much for the accepted methods of increasing speed range. The method under discussion in this paper can not be properly classified under any of these headings. In conception, however, it is derived from variable surface, though the mechanical device utilized is distinctly variable camber.

Let us return to the conception of variable surface. A machine so equipped would have a comparatively small amount of fixed surface, together with a larger amount of removable surface. While landing, both fixed and removable surface would be in operation, but at high speeds the fixed surface alone would support the machine. Assuming that a mechanical device to operate such a system is possible, it is obvious that the mechanism would entail a considerable increase in weight, and probably also in head resistance. This may be expressed in terms of the resistance of the wings that have been removed. For example, 100 units of drag may have been eliminated by removing a portion of the wings, but the equivalent of 20 added by the extra weight and increased resistance. This, then, would leave us a net saving of 80 units.

Suppose, now, that instead of removing the wings we leave them in place, but when they are not required for lifting we change them to a shape offering only a fraction of their former drag. If this fraction is approximately the same as that required for variable surface we will have all the advantages of variable surface, and the problem will become one of changing the wing from an efficient lifting shape to a shape offering the least possible resistance; for example,

pure stream line. Experimental results show that such a saving can be effected; the drag can be reduced from 100 units to 25, giving us a net saving of 75 units. In a biplane the upper plane will be of fixed construction and the lower one variable, or vice versa; while in a triplane a suitable arrangement is obtained by using a fixed wing for the center plane and placing variable wings above and below it. At high speeds the variable planes are to carry no load and are to be stream line in shape. At low speeds they are to bear their share of the weight of the machine and are to be deeply cambered. For a stream-line wing to give no lift it must lie parallel to the direction of the air flow, and then the forces on its upper and lower surfaces are equal. It is necessary, therefore, to set the stream-line planes at zero angle of attack when the fixed planes are at their angle of maximum lift/drag, usually about 3°.

For slower speeds the angle of attack of the fixed plane must be increased, let us say, from 3° to 9°, a change in angle of 6°. The stream-line plane is carried through the same angle and now has unbalanced forces acting on it, tending to deform it upward. These forces are the greatest near the leading edge, and decrease rapidly as the trailing edge is approached. If we place one wing spar at the leading edge and another about two-thirds of the chord back from it, we divide the wing into two parts, with the force on the front part very much greater than that on the rear part. If, now, we make the part between the spars of flexible construction and the part behind the rear spar rigid, and allow the ribs to slide over the rear spar, we provide for a change of shape under load. The portion between the spars is carried upward, while the rear portion, being rigid and fixed to it, moves downward. The result is a cambered wing.

The rib should be just rigid enough to deform a certain desired amount under the maximum load it should carry normally, and the deformation should be proportional to the load upon the rib up to full load. The load at any time will depend on the ratio of the lift coefficient of the variable plane at its angle of attack to the lift coefficient of the fixed plane at its angle. Thus, at maximum speed when the variable plane is stream line in shape the proportion is zero to the lift coefficient of the fixed plane, and the load is zero. At landing speed the lift coefficients of the two planes are approximately equal—the variable plane is carrying half the load and its load and deflection are a maximum. In an intermediate case, when the planes are at 6° and 9°, respectively, the lift coefficients are, let us say, 1:3. The variable plane is now carrying a quarter of the load, or one-half its maximum load, and its shape will be halfway between the extremes. It is now a lifting aerofoil, but a lightly cambered one. As lightly cambered aerofoils are most efficient at small angles, and heavily cambered ones at large angles, the variable wing possesses the most suitable shape throughout its range.

If the decalage remained unchanged, i. e., if the setting of the variable plane relative to the fixed plane remained the same for all angles of attack, when the fixed plane was at its angle of maximum lift the variable plane would be 3° short of it, and would not be operating under the best conditions. This is not the case, however. In changing the shape of the wing the trailing edge was depressed and the angle of attack in consequence was increased. This change in decalage is dependent on the position of the rear spar and on the amount of maximum camber. In the aerofoil used it is 3°, so that when the maximum lifting effort is required both fixed and variable planes are operating most efficiently.

It is obvious that under certain conditions—gusts, for example, or flattening out after a steep dive—the wing will be subject to a load greater than its normal maximum. This would be liable to cause further deflection, which would be undesirable. The wing under discussion ceases to deflect after the application of its normal maximum load. This is accomplished by means of an internal bracing system which only comes into operation when the maximum deflection has been reached.

RIB STRUCTURE.

In designing a wing possessing these variable camber features the following considerations had to be kept in mind:

It had to deform regularly with the load up to unit flying load, then remain rigid under further applications of load, and be strong enough to bear several times its normal load without failure. It had also to be capable of easy manufacture, to be simple and foolproof in operation,

and light in weight. Metal construction was practically a necessity, and to avoid new features which might be doubtful engineering practice, standard construction was adhered to wherever not essential to the functioning of the device. The ribs were thus the only parts of the wing requiring alteration, leaving spars, bracing wires, struts, etc., substantially as at present. Figure 1 shows the general construction adopted. The essential parts are:

1. Channel-shaped strips *A*, *B*, forming the upper and lower surfaces of the rib between the spars.

2. Compression links at *C*, *D*, *E*, *F*, and *G*. These are also of channel section and are fixed to the outer channels by pins, thus allowing the necessary angular motion between links and strips.

3. Tension links *H*, *J*, *K*, *L*, *M*, and *N*. These are flat strips of steel attached to the same pins which carry the compression links. In the stream-line position they carry no load and bow as shown, but in the lifting position they straighten out and make a truss of the rib, preventing further deformation under overloads. The links in the first two and last two panels are slotted to allow the insertion of reverse links.

4. Reverse tension links *O*, *P*, *Q*, and *R*. The only function of these is to prevent the rib being deformed beyond its stream-line position when subject to loads on the upper surface.

5. A tailpiece, fixed in shape, riveted to the upper strip at *S* and constructed to slide over the rear spar.

6. A spring placed between the rear spar and the tailpiece. Provided the channels *A* and *B* are made of sufficient size, a rib can be made which will function properly without this spring, but its use effects a considerable saving in the total weight of the rib. The spring used is a helical tension spring attached to the rear spar and to the front compression member of the tailpiece.

The upper and lower surfaces are fixed to the front spar, which is placed practically at the leading edge. A light wooden nose piece running the length of the wing and attached to the spar gives a fair shape to the leading edge. The rigidity of the rib, due to the stiffness of the channels and the spring, must be such that it attains its full lifting form under normal flying load. The lengths of the tension links determine the final contour of the wing.

The fabric is continuous over the wings except where the lower flexible channel is connected to the tailpiece. Here it is discontinuous to permit the sliding forward of the fixed tail portion over the end of the channel forming the flexible portion of the lower surface. The amount of this sliding motion is approximately 1 inch, and it may be provided for either by allowing the surface to overlap or simply by leaving a gap of this amount. In the former case the surfaces would just meet when in the stream-line position and would overlap 1 inch in the lifting position. In the latter case they would meet when in the lifting position but in the stream-line position would leave open a strip 1 inch wide running the length of the wing. It is not believed that this would be as objectionable as might appear at first sight, for the aerodynamic properties of the wing would not be appreciably affected. Present methods may be used for its attachment to the ribs. It will probably be preferable to stitch the fabric to each surface separately, though there is no objection to the stitching going over the top and under the bottom, except at the rear spar, as the distances between the surfaces do not alter. It was necessary to determine whether any excessive stretch in the fabric would be caused by the functioning of the ribs. The lower surface changes from a convex to a concave shape of approximately equal curvature. There will, therefore, be no stretch in the fabric. In the upper surface, however, where an increase of convex curvature occurs, there will be a stretch caused in the fabric. Calculation shows that this is not serious. In a wing of 60-inch chord, with a maximum increase of camber of 2½ inches, the maximum stretch of the fabric is only 1/100 inch in the 15 inches in which the greatest change occurs, or 0.067 per cent. As the stretch at rupture is 15 per cent, the fabric is only strained 1/225 of this amount. It is reasonable to suppose that this could be repeated indefinitely.

VARIABLE CAMBER RIB

RIB TESTS.

CONDITIONS OF TEST.

The construction and testing of the variable camber rib were carried out in the Engineering Materials Laboratory of the Bureau of Standards. A special method of testing the rib had to be devised, permitting the appropriate load to be applied to each surface independently. A direct system of loading was adopted, the method being clear from figures 2 and 3. Stirrups were placed over the rib at the desired points and platforms to carry the weights suspended therefrom. The loads applied were calculated from pressure distribution tables for the R. A. F. 14 wing, obtained from experiments made at the Royal Aircraft Factory, England.

The chord of the variable rib was 60 inches. The rib spacing was taken as 14 inches and the wing loading as $5\frac{3}{4}$ pounds per square foot. This gives the total load per rib as $33\frac{1}{2}$ pounds, which was assumed to be distributed as follows:

UPPER SURFACE.

Distance from leading edge, in inches	$4\frac{1}{2}$	$10\frac{1}{2}$	$17\frac{1}{2}$	24	30	36	42	48	54
Load, in pounds	4	4	$4\frac{1}{2}$	3	$2\frac{1}{2}$	2	2	1	1

LOWER SURFACE.

Distance from leading edge, in inches	$1\frac{1}{2}$	$7\frac{1}{2}$	$20\frac{1}{2}$	33
Load, in pounds	$3\frac{1}{2}$	$3\frac{1}{2}$	$1\frac{1}{2}$	1

The applied loads were correct to the nearest half pound and the points of application were correct to the nearest half inch. Within these limits the loading checked the pressure distribution figures on which it was based.

RESULTS OF TESTS.

	Ounces.
Weight of rib, bare	$11\frac{1}{2}$
Weight of helical spring	$\frac{3}{4}$

The total weight of the rib is thus $12\frac{1}{4}$ ounces, which compares very favorably with standard wood construction. It is actually lighter than the Curtiss JN–4 rib ($13\frac{1}{2}$ ounces), which was taken as a basis for chord length, rib spacing, and loading. More modern ribs, however, are somewhat lighter.

Material used, chrome vanadium alloy steel.
Thickness, 0.018 inch.
Elastic limit, 90,000 pounds per square inch.
Ultimate strength, 102,000 pounds per square inch.

The steel as fabricated was in the annealed state. In some earlier tests heat treatment was resorted to, and, as might be expected, gave even greater strength, two such ribs having sustained a loading of 16 times the flying load without signs of failure. Heat treatment was omitted in the final test in order to demonstrate that the process was not essential to success.

The experimental rib was placed in an inverted position in a supporting frame and the loads applied as previously described. Deflection readings were taken by means of dials giving readings correct to 1/1000 of an inch. Up to unit load, the increments were one-quarter of the flying load. The deflection of the rib under these conditions was as follows:

Load.		Deflection.					
		At distances from leading edge of—					
Portion of normal flying load.	Pounds.	$1\frac{1}{2}$-inches (front spar).	12 inches.	21 inches.	30 inches.	39 inches (rear spar).	60 inches (trailing edge).
		Inch.	*Inches.*	*Inches.*	*Inches.*	*Inch.*	*Inches.*
$\frac{1}{4}$	$8\frac{3}{8}$	0	0.54	0.60	0.39	0	−0.90
$\frac{1}{2}$	$16\frac{3}{4}$	0	1.00	1.06	.69	0	−1.46
$\frac{3}{4}$	$25\frac{1}{8}$	0	1.37	1.47	.94	0	−1.94
1	$33\frac{1}{2}$	0	1.83	2.03	1.39	0	−2.53

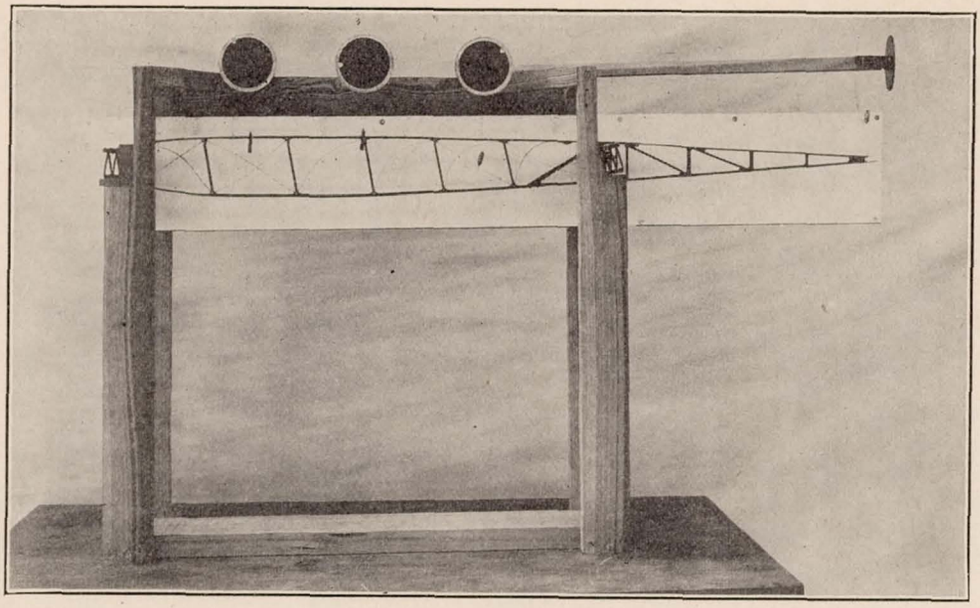


Fig. 2.

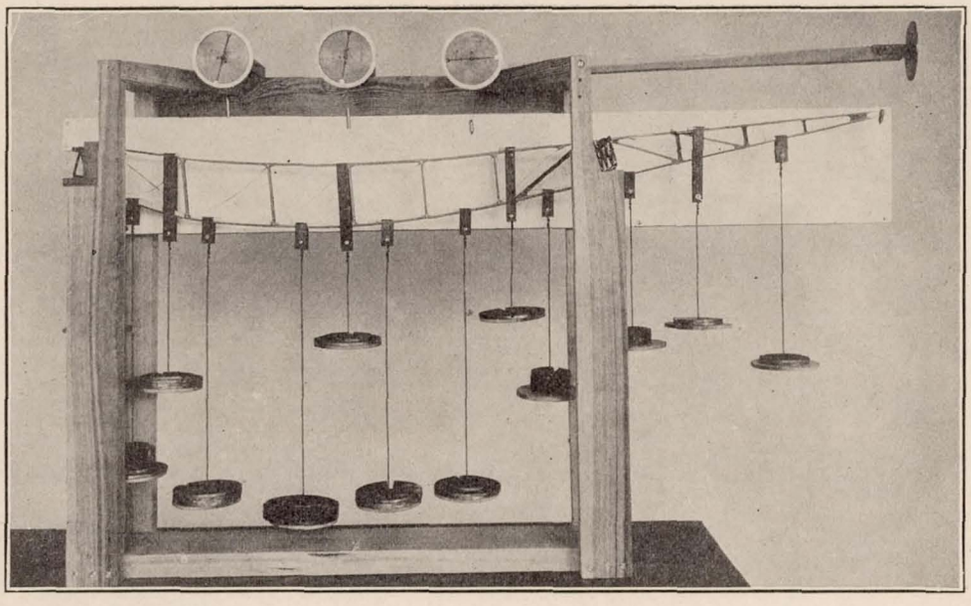


Fig. 3.

Weights were then applied up to six times the flying load. After this the loading was removed, with the exception of the one-quarter load, to determine the ability of the rib to return to its original shape after severe overloads. A permanent set amounting to a maximum of $\frac{5}{32}$ inch occurred in the first and second panels. Throughout the rest of its length the rib returned to the position occupied under the initial one-quarter load.

Finally the rib was loaded to destruction. Failure occurred after the application of a load corresponding to 11 times the flying load by buckling of the flanges of the lower surface in the

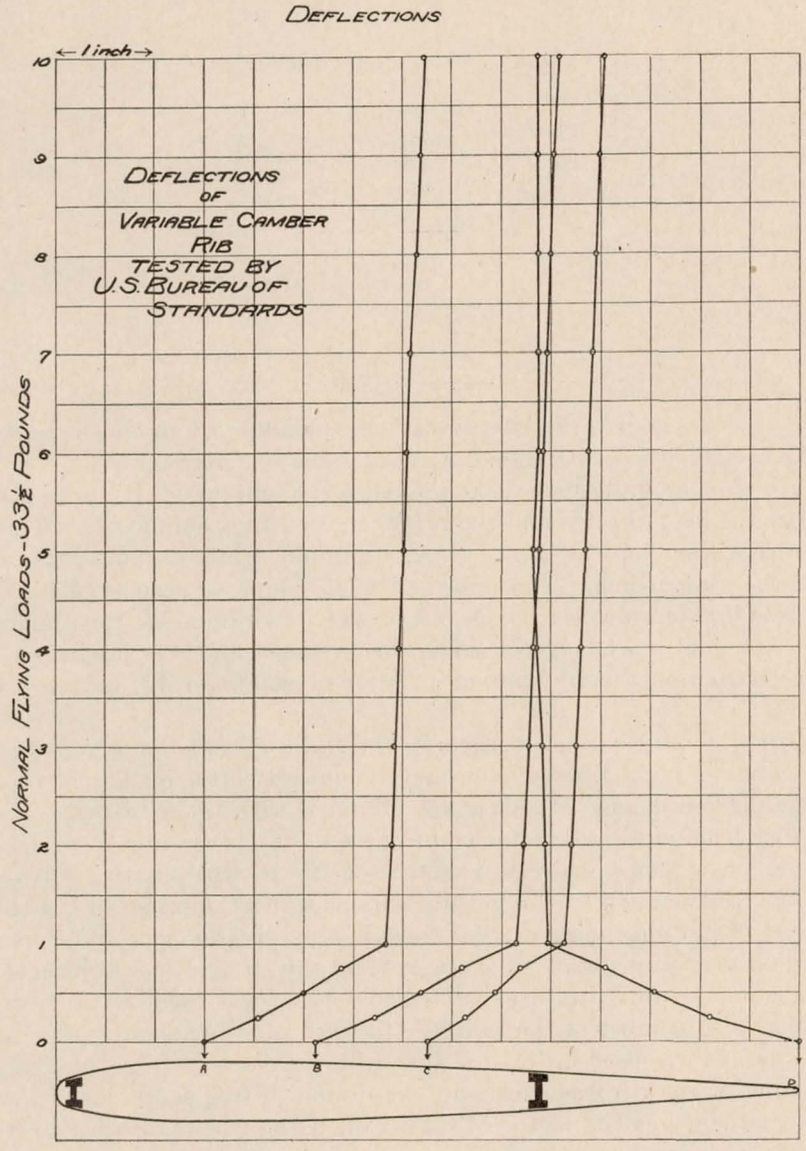


Fig. 4

first and second panels. Deflections are plotted in figure 4 and tabulated in the appendix. The maximum deflection from normal flying load to 10 times that load was 0.437 inch, which compares favorably with that of wooden ribs under similar loads. While subject to the normal flying load, the shape of the rib was traced upon a board placed behind it. Its form agreed (within $\frac{1}{8}$ inch) with the designed aerofoil (V. C. L., fig. 6).

The rib which gave these results was the last of a series of six. It is not claimed that it represents the best possible form for such a rib, but marks a point in the development where the many conflicting requirements are all satisfied.

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The first two ribs of the series were made from steel 0.032 inch in thickness and were heat treated. The lifting shape aimed at was the Eiffel 36-wing curve. The spars were placed in the same positions as in the Curtiss JN–4 and the nose was designed to rotate about the front spar. The variable portion was divided into four panels, of which three only were provided with tension-bracing members. The weight was 16 ounces. A change of shape approximately proportional to the load was obtained, but the tail failed to deflect its full amount and the rotary motion at the nose was found unsatisfactory. The functioning of the rib is shown by the following deflection readings:

Load.	Deflection.	
Fraction of normal flying load.	Mid-point between spars.	Training edge.
	Inches.	*Inches.*
¼	0.35	0.40
½	.80	.95
¾	1.14	1.48
1	1.40	1.90

The strength was excessive, the ribs sustaining a loading of 16 times the flying load, the limiting capacity of the supporting frame, without signs of failure.

The third rib was of 0.018-inch heat-treated steel and weighed 11 ounces. The front spar was placed at the leading edge and the rotary motion thus eliminated. The upper surface was designed to have the shape of the U. S. A. 4 aerofoil, while the lower was determined by the thickness of the stream line. The nose had to be blunt to accommodate the spar. The flexible portion was divided into six panels, all of which were braced, thus making a complete truss of the rib. The desired change of shape was attained and was proportional to the load. When tested to destruction the rib showed a factor of safety of 11, failure occurring in the fixed tailpiece.

The fourth rib was similar in all respects to the third, except that it was not heat treated. It withstood a loading of eight times the normal flying load before buckling over sideways.

Although the desired change of shape was obtained with these two ribs, the lifting shape was not satisfactory from an aerodynamic point of view. Consequently a special lifting aerofoil was designed, and an attempt made to construct a rib to this shape. 0.018-inch steel was again used and the construction was in general similar to that adopted in the third and fourth ribs. The amount of motion, however, was considerably greater, and additional tension links were provided to prevent any change of shape beyond the stream-line position should the wing be subject to loads on the upper surface. A tension spring was used, attached to the rear spar and to the compression member of the tailpiece forward of it, instead of a compression spring behind the rear spar, as was used in the first four ribs.

The functioning of the rib was excellent, the desired lifting shape being assumed with an error of less than ⅛ inch, but the factor of safety when the rib was loaded to destruction was only 7. Failure was due to buckling in the channel forming the lower surface in the first and second panels. The weight was 12 ounces.

The behavior of this rib under fractional loads was as follows:

Load.		Deflection.					
Portion of normal flying load.	Pounds.	At distance from leading edge of—					
		1½ inches (front spar).	12 inches.	21 inches.	30 inches.	39 inches (rear spar).	60 inches (trailing edge).
		Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
¼	8⅜	0	0.45	0.42	0.20	0	−0.45
½	16¾	0	.99	1.02	.57	0	−1.20
¾	25⅛	0	1.44	1.55	.95	0	−1.82
1	33½	0	1.82	1.98	1.25	0	−2.42

The final rib differed only in minor details, particularly the use of a heavier flange at the point of failure. This raised the factor of safety from 7 to 11 at an increase of only ¼ ounce in weight.

AERODYNAMICAL TESTS.

A series of tests were carried out by the Bureau of Standards wind tunnel staff to determine the following points:

1. The properties of four new aerofoils, being the stream-line and full-lifting shapes of the variable camber wing, and two intermediate shapes under one-third load and two-thirds load, respectively.

2. The aerodynamic efficiency of these aerofoils when used together with a standard aerofoil in biplane and triplane combinations.

3. The stability of these biplane and triplane combinations.

Models of the necessary aerofoils were made of bakelite and were correct to within five one-thousandths of an inch. The model of R. A. F. 6, which was used as the standard section, was of wood, and though accurate when made did not retain its accuracy as well as the bakelite models.

The stream-line and full-lifting aerofoils were designed in accordance with certain limitations imposed by the rib structure. The chief of these were:

1. The necessity for a blunt nose to permit the front spar being placed at the leading edge.

2. In the lifting model a lower surface concave toward the trailing edge could not be used because the portion of the rib behind the rear spar does not change shape and the stream line is slightly convex.

3. The camber of the lower surface between the spars was limited by the necessity of allowing for internal bracing wires.

4. The maximum camber on the upper surface was determined by the camber of the lower and by the thickness of the aerofoil, which, in turn, was determined by the fineness desired in the stream line.

The two extreme shapes were carefully designed in the light of these and of aerodynamical considerations. The intermediate shapes were obtained on the assumption that the rib deflected throughout its length directly as the load up to normal full load. Control can be exercised over the design of these intermediate shapes by varying the depth of the flanges of the rib channels, but as the distribution of pressure is also a factor and as it is not known how much the distribution assumed (R. A. F. 14) differs from the actual, the shapes used were arrived at somewhat arbitrarily.

The wind tunnel used at the Bureau of Standards is of 54-inch octagonal section, the air being drawn through by a 100-horsepower motor. The balance is of the N. P. L. type and the

models were mounted vertically in the tunnel. In the biplane and triplane combinations the models were spaced relatively by brass struts screwed into the ends. Provision was made for a fine adjustment of the decalage by the arrangement illustrated in figure 7. The points of attachment of the struts to the variable planes corresponded approximately with the positions of the spars in the full-size wing. The leading edge was thus fixed in position, so no adjustment for gap was necessary. The chord of the fixed middle aerofoil was used as a reference plane, and the decalage measured by the difference in gap at the trailing edge.

Lift, drag, and torque determinations were carried out on the following aerofoils and combinations:

Aerofoil V. C. stream line (*a*) used afterwards in biplane and triplane tests; V. C. stream line (*b*) used in triplane tests only.

Aerofoil V. C. one-third lifting (*a*) used in biplanes and triplanes; V. C. one-third lifting (*b*) used in triplanes only.

Aerofoil V. C. two-thirds lifting, used in biplane tests.

Aerofoil V. C. lifting (*a*) used in triplanes and biplanes; (*b*) used in triplanes only.

Aerofoil R. A. F. 6, used in biplanes and triplanes.

Biplanes.

No.	Lower plane.	Upper plane.	Stagger.	Decalage.
			Per cent.	*Degrees.*
1	R. A. F. 6	V. C. S	−20	2½
2	R. A. F. 6	V. C. ⅓ L	−20	1½
3	R. A. F. 6	V. C. ⅔ L	−20	½
4	R. A. F. 6	V. C. L	−20	−½
5	V. C. S	R. A. F. 6	+20	2½
6	V. C. ⅓ L	R. A. F. 6	+20	1½
7	V. C. ⅔ L	R. A. F. 6	+20	½
8	V. C. L	R. A. F. 6	+20	−½

Triplanes.

No.	Top plane.	Middle plane.	Bottom plane.	Stagger.	Decalage.
				Per cent.	*Degrees.*
1	V. C. S	R. A. F. 6	V. C. S	20	2½
2	V. C. ⅓ L	R. A. F. 6	V. C. ⅓ L	20	1½
3	Test—not run				
4	V. C. L	R. A. F. 6	V. C. L	20	−½

The term decalage here refers to the incidence of the planes of the variable series to the chord line of the standard plane.

Detailed results will be found tabulated in the appendix at the end of the report.

DISCUSSION OF WIND-TUNNEL RESULTS.

SINGLE AEROFOILS.

The curves for the variable wing as a monoplane (fig. 8) were obtained from figures 14, 15, and 16. At low angles (−3°, −2°, −1°, 0°), when the variable wing was stream line, the points for the variable curves were obtained from the curves for V. C. S. At high angles (12°, 14°, 16°, 17°, 18°), when it was in its full lifting shape, the points from V. C. L. were used. Two intermediate sets of points were obtained—one from the curve for V. C. ⅓ L. at 4° and the other from the V. C. ⅔ L. curves at 8°.

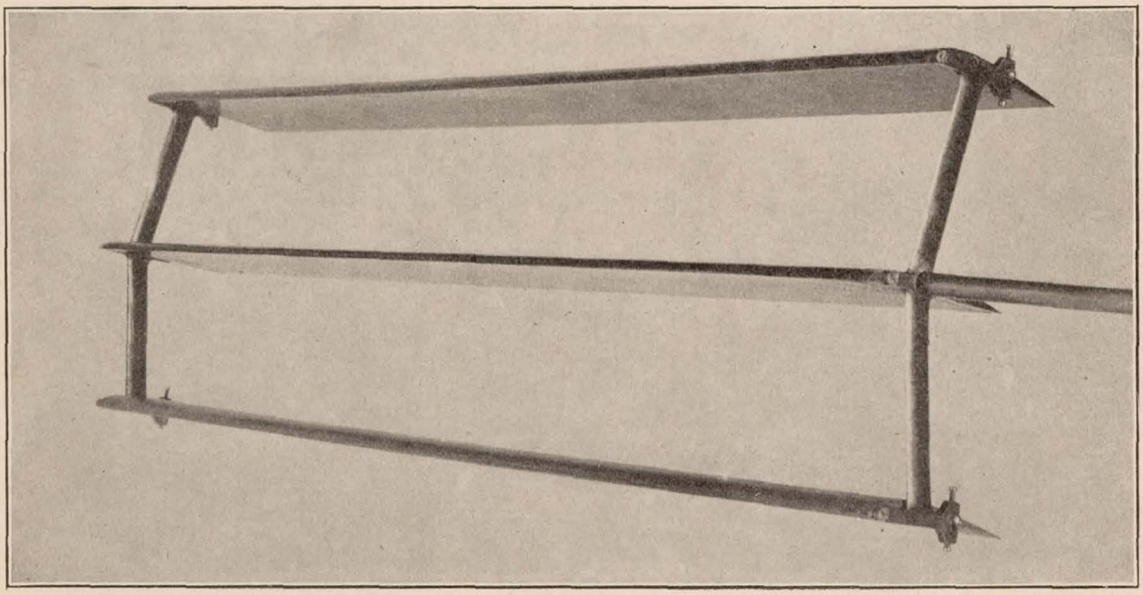


Fig. 7

The travel of the center of pressure is noteworthy, being as nearly as possible stationary—the amount of travel within the range of flying angles being 0.035 chord in the stable direction. Aerofoils of the fixed type are unstable. Thus, if the center of pressure coincides with the center of gravity at any angle within the flying range, the plane will be in equilibrium. If, however, it is then displaced from this angle, the position of the center of pressure will change and will introduce an upsetting moment which will move the plane still further from its position of equilibrium. This unstable effect is very marked at small angles of incidence. This is apparent from figure 16, the curves for V. C. $\frac{1}{3}$ L., V. C. $\frac{2}{3}$ L., and V. C. L. being typical of all ordinary aerofoils. In figure 8 the motion of the center of pressure is such that if the plane be displaced from its angle of equilibrium the resulting moment will tend to bring it back to that position. At 17° a marked change occurs, but this is evidently due to the breakdown in the air flow which takes place at that angle, and which is also noticeable in the lift and drag curves. The individual curves (figs. 14, 15, and 16) are characteristic for the particular types of aerofoils, though the intermediate shapes are somewhat inefficient when compared with other aerofoils of similar camber.

The drag curve (fig. 15) shows that the minimum resistance of the stream-line plane is less than one-third that of the lifting plane. These are the figures for the models at the tunnel speed of 50 miles per hour. In a full-size machine, traveling at 150 miles per hour, the minimum drag would be about one-quarter. This improvement at high speed is due to the fact that the drag of an aerofoil is made up of two parts—the direct head resistance, which increases as the square of the speed, and the skin friction, which increases at a lesser rate. The drag of a stream-line body is mostly skin friction, while that of a heavily-cambered aerofoil is nearly all direct head resistance. Variable camber, therefore, gives us a wing having the high lift coefficient of V. C. L. with the objectionable high minimum drag of such a wing cut down by 75 per cent.

BIPLANES.

The first biplane series, with the variable wing for the upper plane and with the negative stagger, shows excessive stability. The vector diagram (fig. 11) was obtained by assuming a center of pressure travel by plotting a curve through the appropriate points in figure 19. Up to 2½° the variable plane is stream line, at 4½° it is assumed to be one-third lifting, at 8° to be two-thirds lifting, and 12° to be full lifting.

If the planes were attached to the machine so that the center of gravity was situated at a point on the vector for 2°, and slightly above the lower plane, the arrangement would be stable under all conditions. Thus, if the incidence was increased to 18°, a moment would come into play tending to reduce the incidence, while if it was reduced to 0°, the resulting moment would cause it to be increased. Even in the abnormal position represented by the vector for −1° there would still be a correcting moment to bring the machine back to its position of equilibrium. The stability in the case of this biplane is excessive by reason of the correcting moment being too great. There seems no reason why a more satisfactory arrangement should not be obtained with a stagger of 10 or 15 per cent. Forward stagger with this combination, however, would cause very serious instability, as would back stagger in the second biplane arrangement.

This second series, with the lower plane the variable one, and the top plane staggered 20 per cent forward, is very satisfactory. The vector diagram (fig. 12) shows sufficient but not excessive stability, with all the vectors passing practically through a point midway between the planes. The lift curves (fig. 20) are regular, and show no serious falling off at the burble point. No. 8, which is the landing-speed combination, is particularly satisfactory in this respect, having a flat top for 6°. Even after 20°, where the flow does break down, there is a complete absence of the abrupt change which is apparent in the curve for the variable wing as a monoplane. The lift/drag curves (fig. 21) bring out very clearly the advantages of

the variation in camber. Thus the combination with the stream-line plane is most efficient at the small values of the lift coefficient appropriate to very high speeds. Maximum lift/drag is obtained at high but not top speeds, with the variable plane one-third lifting, while for climbing speeds the combination containing the two-thirds aerofoil is most efficient. For landing, as would be expected, the curve for the combination with the full lifting wing surpasses all the others. The inefficiency of this high lift combination, should it be used at high speeds, is very apparent.

Figure 9 is derived from the lift/drag against C_y curves in figures 18 and 21. The base used in this case is *speed*, or $\sqrt{\frac{C_y \text{ maximum.}}{C_y}}$. If C_y maximum is 0.56, it is obvious that when C_y is 0.14 the speed will have to be double that at C_y maximum, in order for the machine to remain in level flight. The curves show actual biplane figures for the variable biplanes. For the R. A. F. 6 biplane, however, a correction was applied to the monoplane figures found for the particular model used in all the tests. The biplane corrections used were those given by Dr. Hunsaker. The figures for lift/drag for all the curves have been corrected for scale effect. The assumptions were made on a basis of a maximum speed of 150 miles an hour and a total area of 400 square feet. A figure for the skin friction of the model was obtained from Zahm's equation:

$$F = 0.0000082\ A^{0.93}V^{1.86}$$

This was subtracted from the corrected balance reading for the drag on the model, and a coefficient derived for direct head resistance. The square law was applied to this portion of the drag, and the total drag was obtained by adding to it the skin friction for the full-size planes, again using Zahm's formula. In the light of some recent full-scale experiments this correction is conservative, but the curves nevertheless show a very marked advantage in favor of the suggested arrangement.

TRIPLANE.

The triplane curves show the same general characteristics as the biplane. The arrangement is stable—rather too much so. A 15 per cent setback of the top and bottom planes should give all that is needed in this respect and at the same time would be slightly better structurally.

SUMMARY.

1. The variable camber wing has a maximum lift coefficient of 0.76 (absolute) and a minimum drag of 0.0070. It has a stable travel of the center of pressure of 0.035 of the chord (fig. 8).

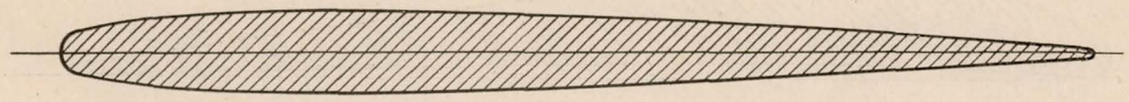
2. At the wind tunnel speed of 30 miles an hour, its minimum drag is less than one-third the minimum drag it would have if the full lifting shape were to be used at small angles of incidence (fig. 15). Under full-size conditions this would be about a quarter.

3. When used in a biplane, the lift/drag is doubled at speeds in excess of 2.1 times the landing speed, and trebled at three times the landing speed. Similar results were obtained in a triplane (figs. 9 and 10).

4. A biplane with 20 per cent forward stagger shows satisfactory stability in the planes themselves. A biplane with 20 per cent back stagger, and a triplane combination, show somewhat excessive stability (figs. 11, 12, and 13).

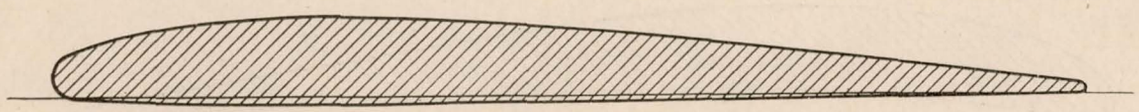
5. The device involves changes in the ribs only.

6. A rib tested at the Bureau of Standards of the same chord length as the Curtiss JN–4. weighed 10 per cent less than that type of rib and showed a factor of safety of 11.



Aerofoil VCS.

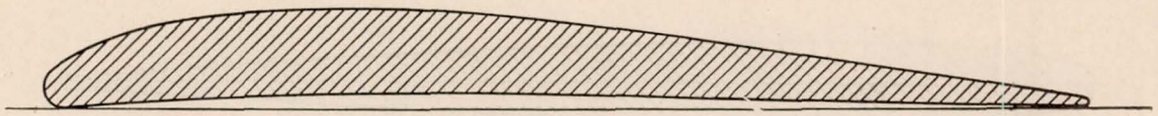
Distance from leading edge.	Length of ordinate.	
	Above chord.	Below chord.
0.00	0.0000	
.05	.0283	
.10	.0358	
.20	.0405	
.30	.0405	
.40	.0377	
.50	.0333	
.60	.0295	
.70	.0236	
.80	.0180	
.90	.0108	
1.00	.0035	



Aerofoil VC⅓L.

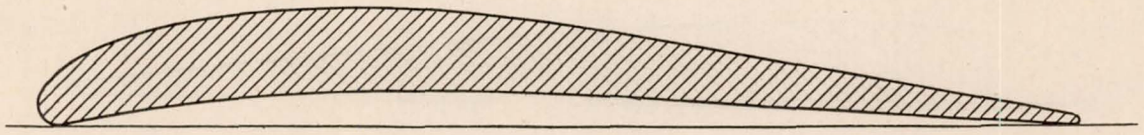
Distance from leading edge.	Ordinates.	
	Upper surface.	Lower surface.
0.000	0.0205	0.0205
.025	.0456	.0000
.050	.0540	.0013
.075	.0600	.0027
.100	.0660	.0037
.200	.0770	.0060
.300	.0773	.0063
.400	.0693	.0056
.500	.0630	.0050
.600	.0546	.0043
.700	.0440	.0037
.800	.0330	.0027
.900	.0304	.0013
1.000	.0070	.0000

FIG. 5



Aerofoil VC$\frac{3}{8}$L.

Distance from leading edge.	Ordinates.	
	Upper surface.	Lower surface.
0.000	0.0205	0.0205
.025	.0483	.0000
.050	.0613	.0021
.100	.0773	.0053
.200	.0915	.0106
.300	.0945	.0153
.400	.0897	.0145
.500	.0803	.0133
.600	.0680	.0096
.700	.0543	.0066
.800	.0396	.0038
.900	.0233	.0019
1.000	.0070	.0000



Aerofoil VCL.

Distance from leading edge.	Ordinates.	
	Upper surface.	Lower surface.
0.000	0.0205	0.0205
.125	.0430	.0017
.025	.0543	.0000
.050	.0695	.0058
.100	.0888	.0152
.200	.1068	.0255
.300	.1114	.0301
.400	.1080	.0316
.500	.0966	.0300
.600	.0816	.0242
.700	.0646	.0173
.800	.0466	.0108
.900	.0268	.0054
1.000	.0070	.0000

FIG. 6.

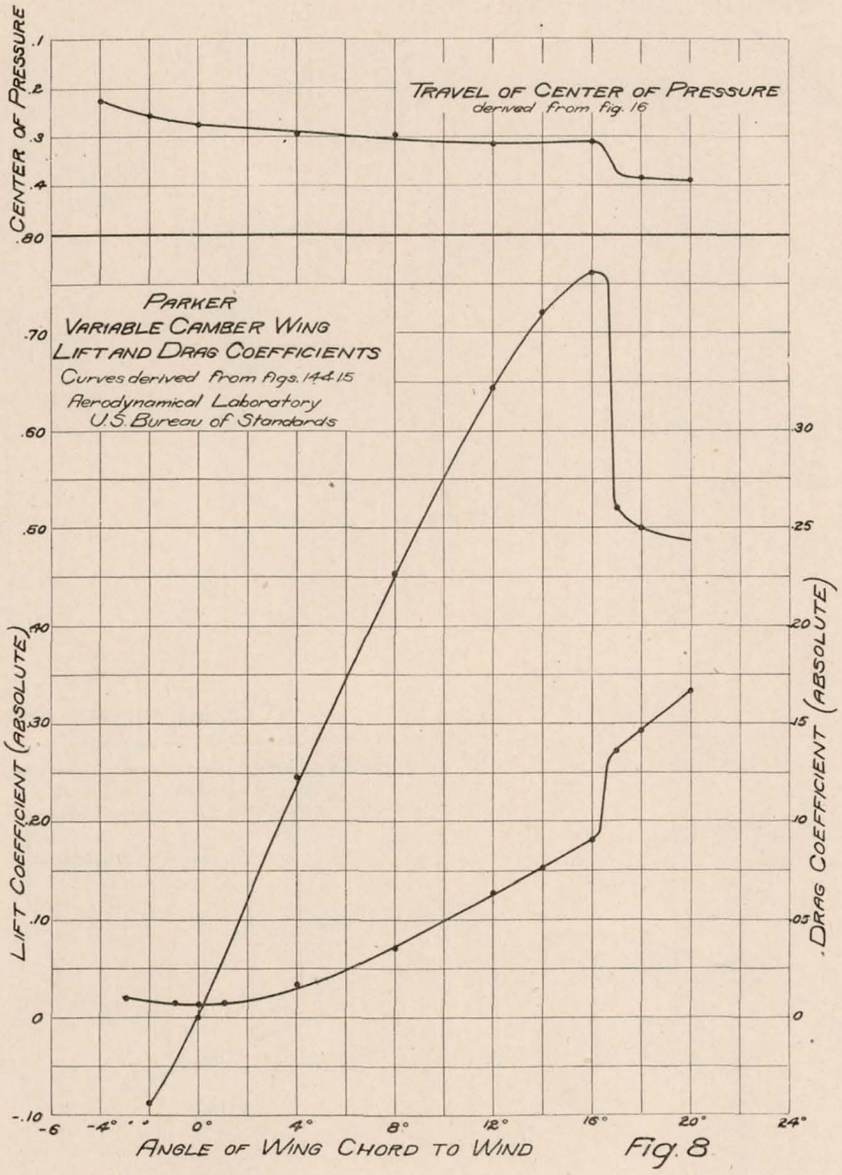

CENTER OF PRESSURE
.1
.2
.3
.4
.80
TRAVEL OF CENTER OF PRESSURE
derived from Fig. 16
PARKER
VARIABLE CAMBER WING
LIFT AND DRAG COEFFICIENTS
Curves derived from Figs. 14 & 15
Aerodynamical Laboratory
U.S. Bureau of Standards
.70
.60
.50
.40
.30
.20
.10
0
-.10
-6
LIFT COEFFICIENT (ABSOLUTE)
.30
.25
.20
.15
.10
.05
0
DRAG COEFFICIENT (ABSOLUTE)
-4°
0°
4°
8°
12°
16°
20°
24°
ANGLE OF WING CHORD TO WIND

Fig. 8

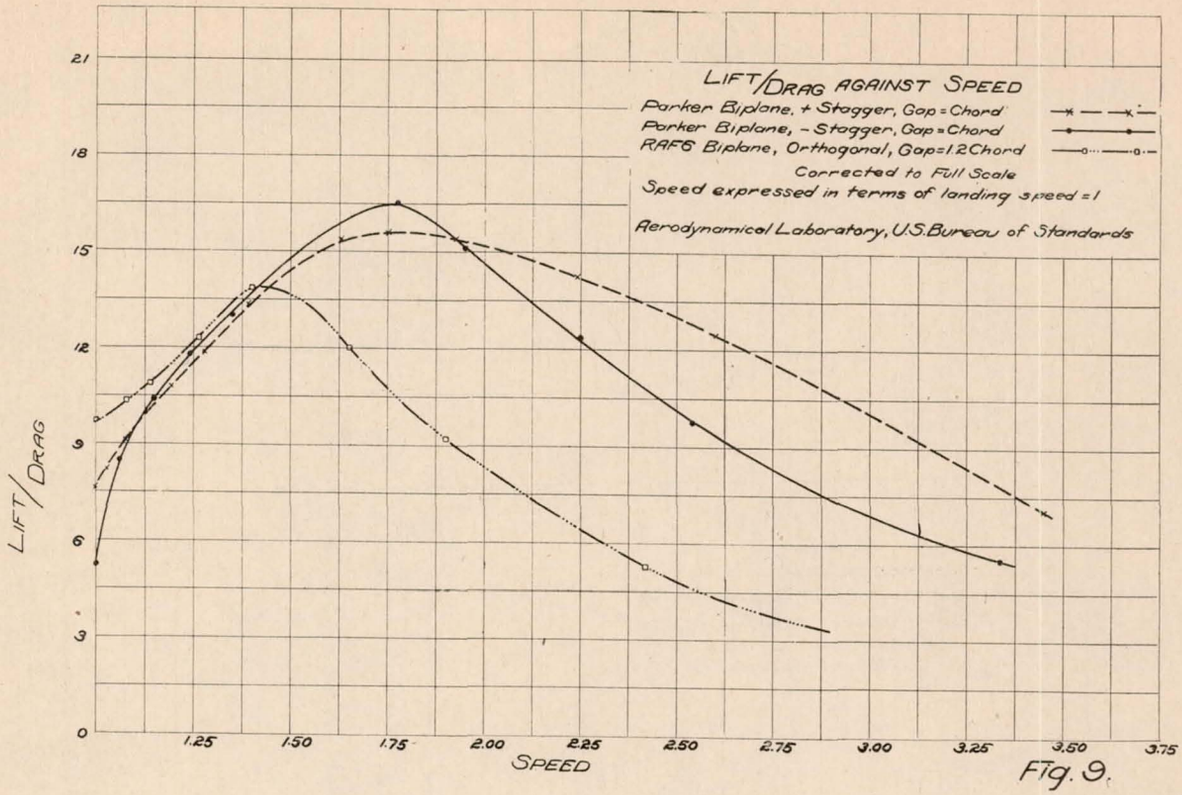

LIFT/DRAG AGAINST SPEED
Parker Biplane, + Stagger, Gap = Chord
Parker Biplane, - Stagger, Gap = Chord
RAF6 Biplane, Orthogonal, Gap = 1.2 Chord
Corrected to Full Scale
Speed expressed in terms of landing speed = 1
Aerodynamical Laboratory, U.S. Bureau of Standards
LIFT/DRAG
SPEED
0
3
6
9
12
15
18
21
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75

Fig. 9.

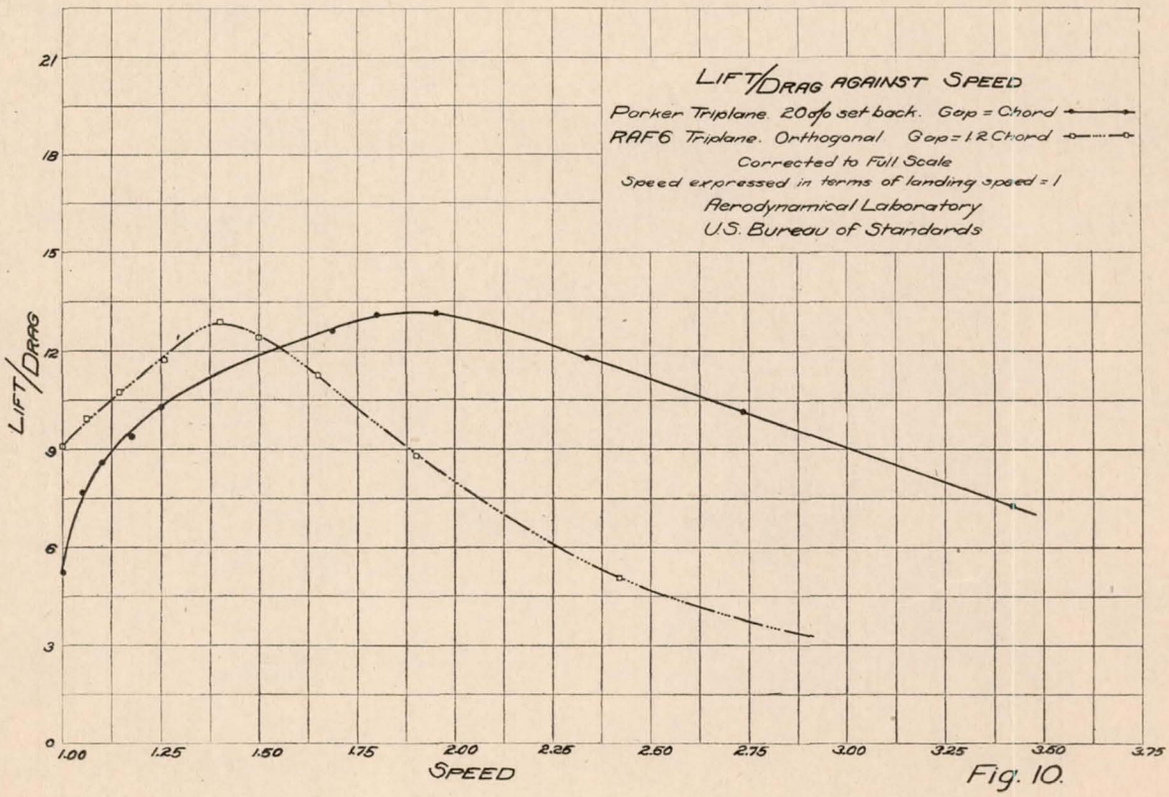

LIFT/DRAG AGAINST SPEED
Parker Triplane. 20% set back. Gap = Chord
RAF6 Triplane. Orthogonal Gap = 1.2 Chord
Corrected to Full Scale
Speed expressed in terms of landing speed = 1
Aerodynamical Laboratory
U.S. Bureau of Standards
LIFT/DRAG
SPEED
0
3
6
9
12
15
18
21
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75

Fig. 10.

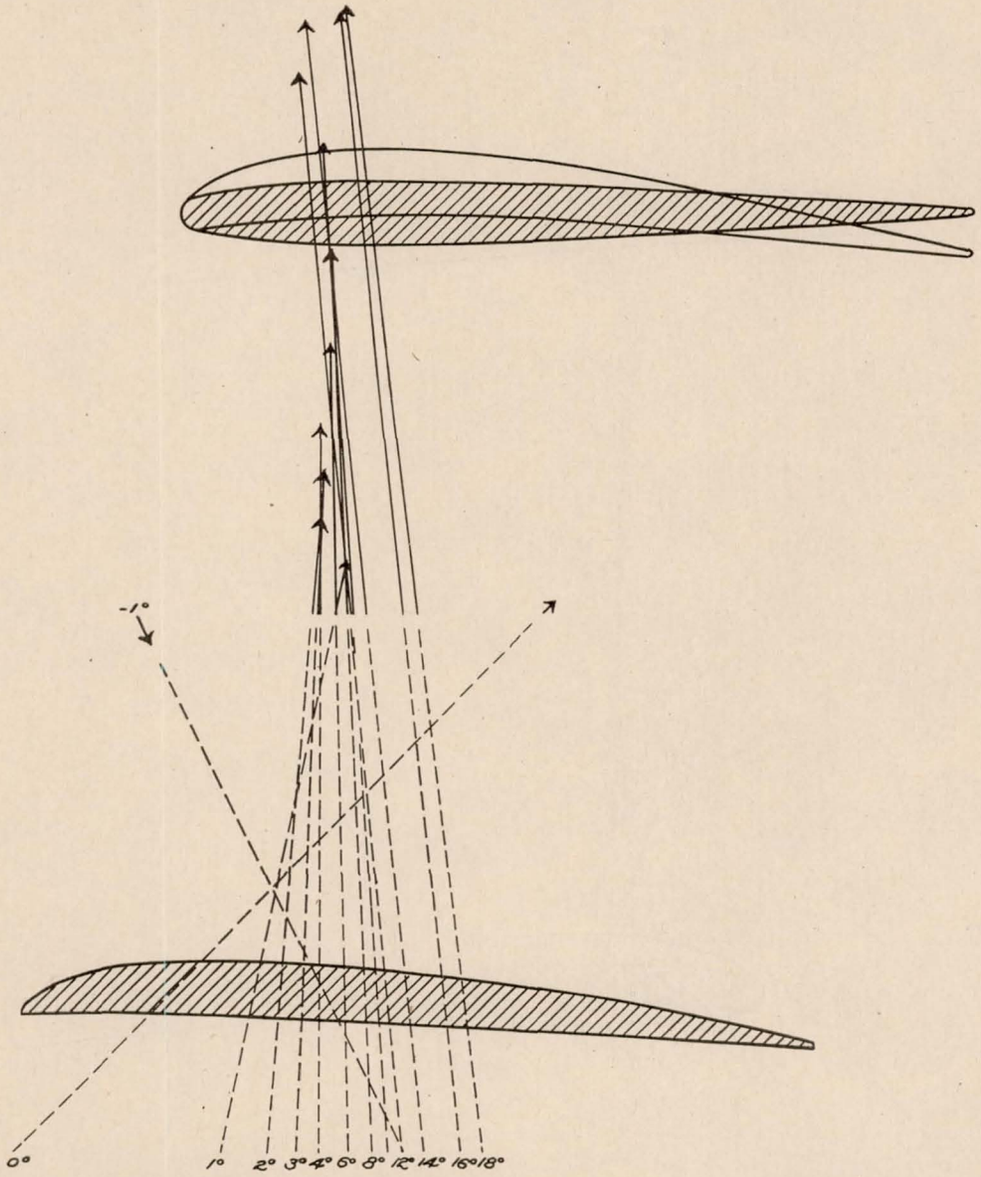


FIG. 11.—Vector diagram for Parker biplane. Upper plane: Variable camber. Lower plane: RAF6. Stagger 20 per cent negative. Gap=chord.

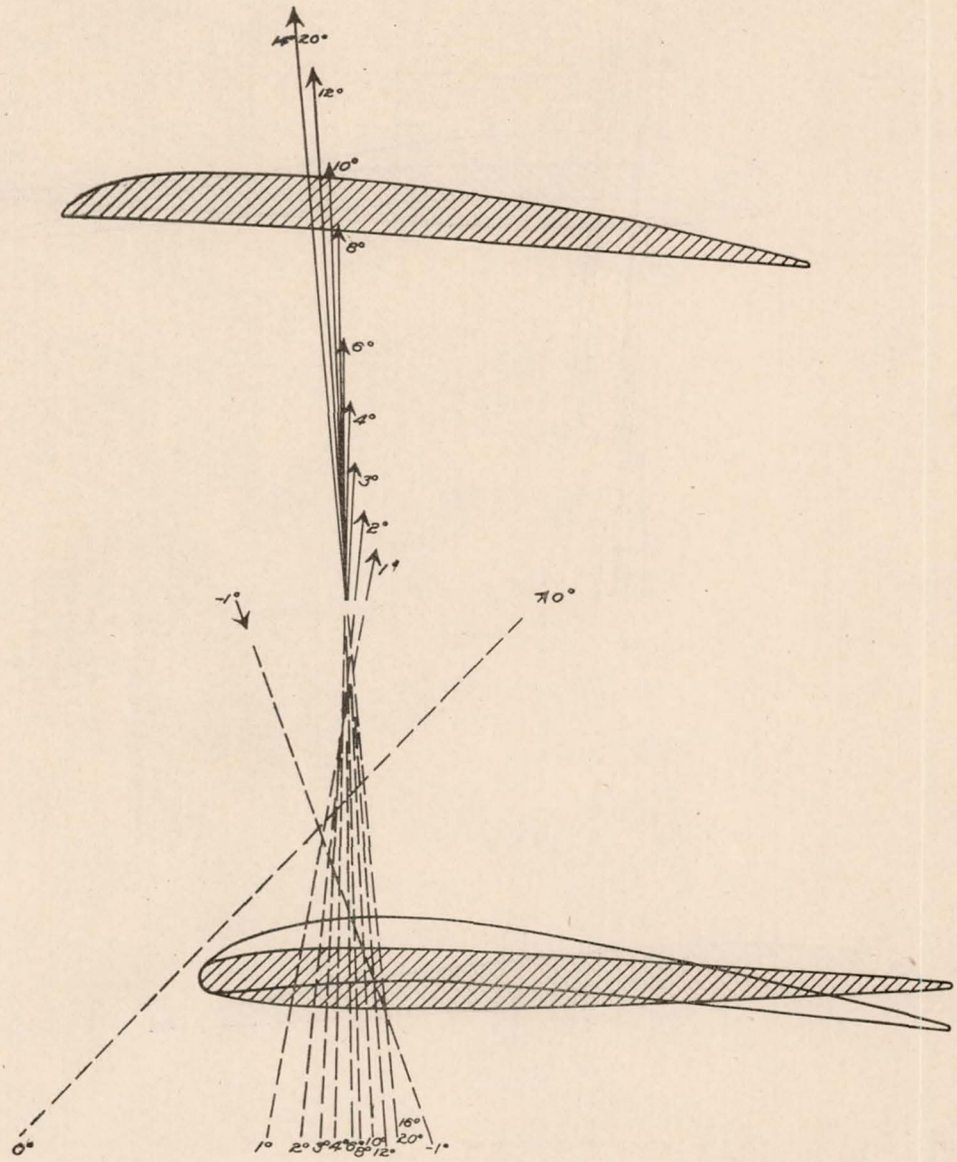


FIG. 12.—Vector diagram for Parker biplane. Upper plane: RAF6. Lower plane: Variable camber. Stagger 2 per cent positive. Gap=chord.

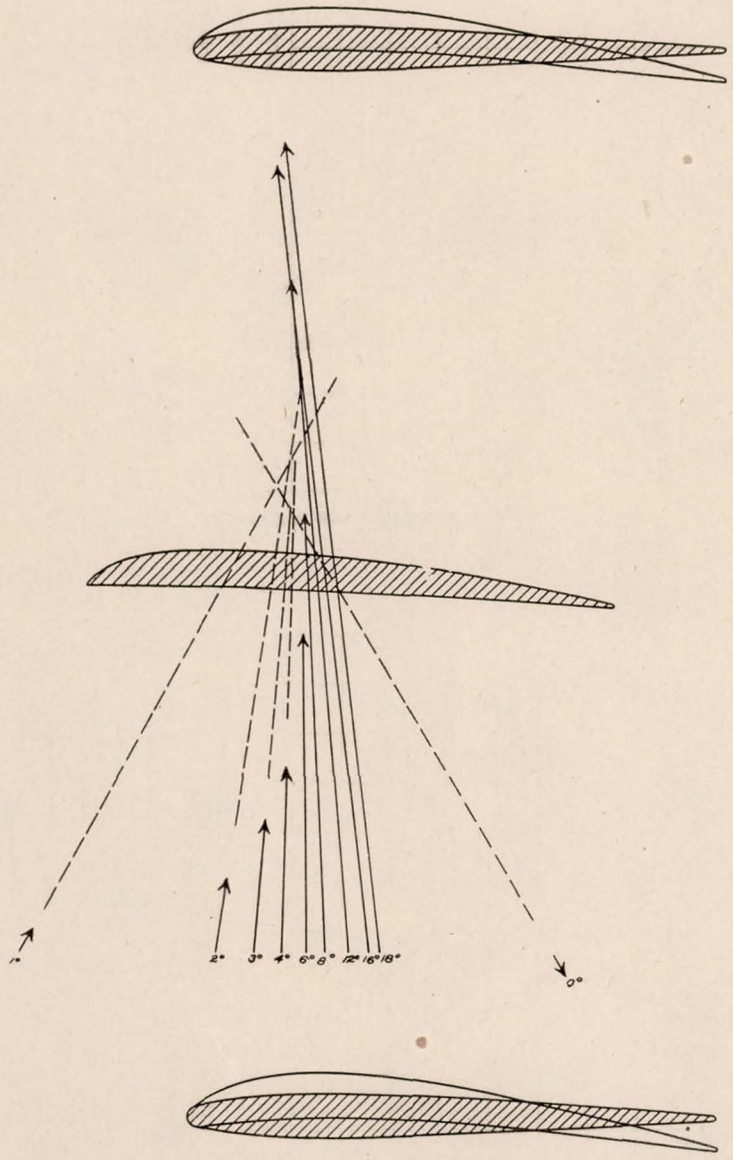


FIG. 13.—Vector diagram for Parker triplane.

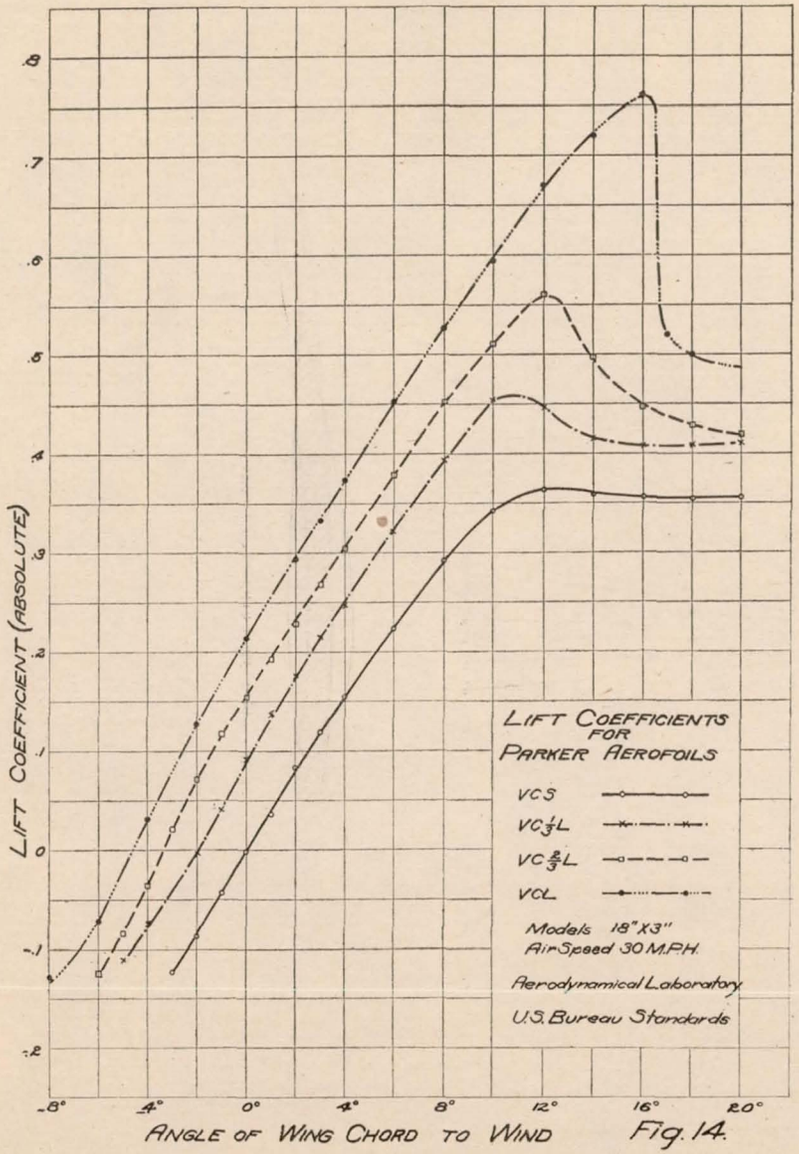

LIFT COEFFICIENT (ABSOLUTE)
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-8°
-4°
0°
4°
8°
12°
16°
20°
ANGLE OF WING CHORD TO WIND
LIFT COEFFICIENTS FOR PARKER AEROFOILS
VCS
VC⅓L
VC⅔L
VCL
Models 18"X3"
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau Standards

Fig. 14.

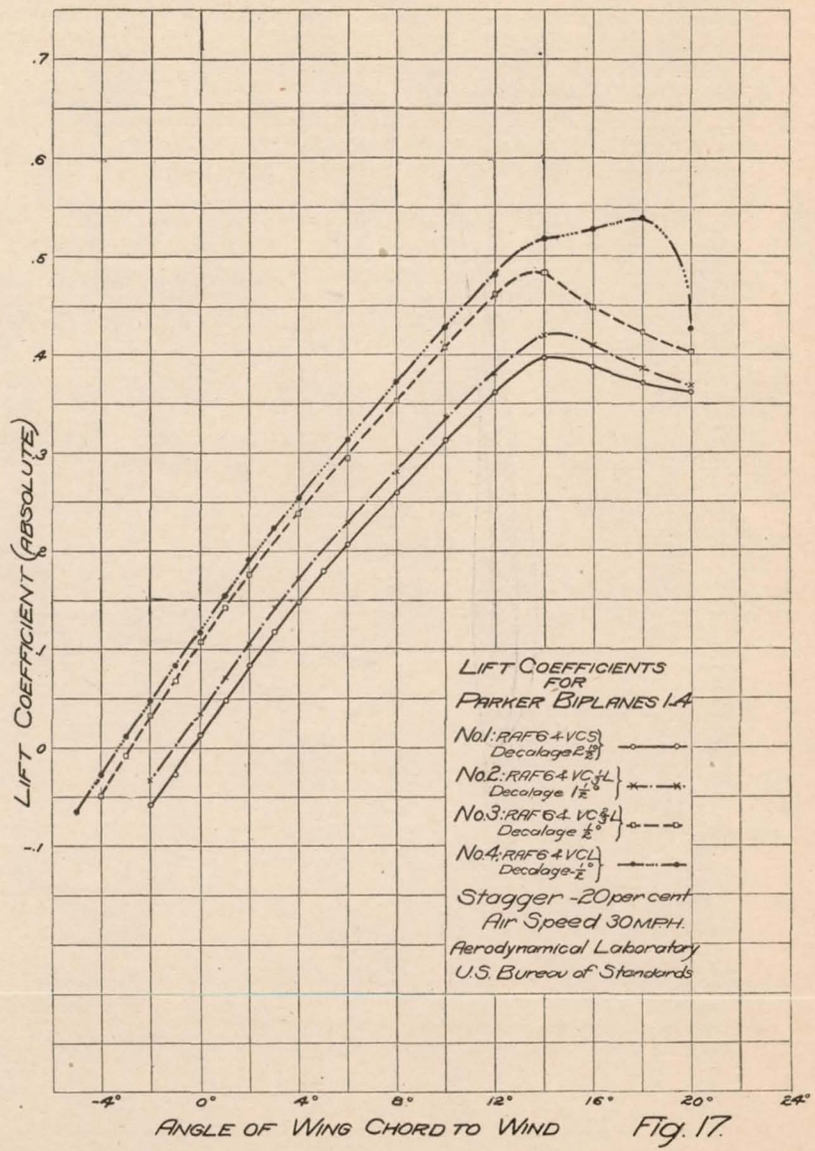

LIFT COEFFICIENT (ABSOLUTE)
.7
.6
.5
.4
.3
.2
.1
0
-.1
-4°
0°
4°
8°
12°
16°
20°
24°
ANGLE OF WING CHORD TO WIND
LIFT COEFFICIENTS FOR PARKER BIPLANES 1.4
No.1: RAF 6 & VCS, Decalage 2½°
No.2: RAF 6 & VC⅓L, Decalage 1½°
No.3: RAF 6 & VC⅔L, Decalage ½°
No.4: RAF 6 & VCL, Decalage -½°
Stagger -20 per cent
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 17.

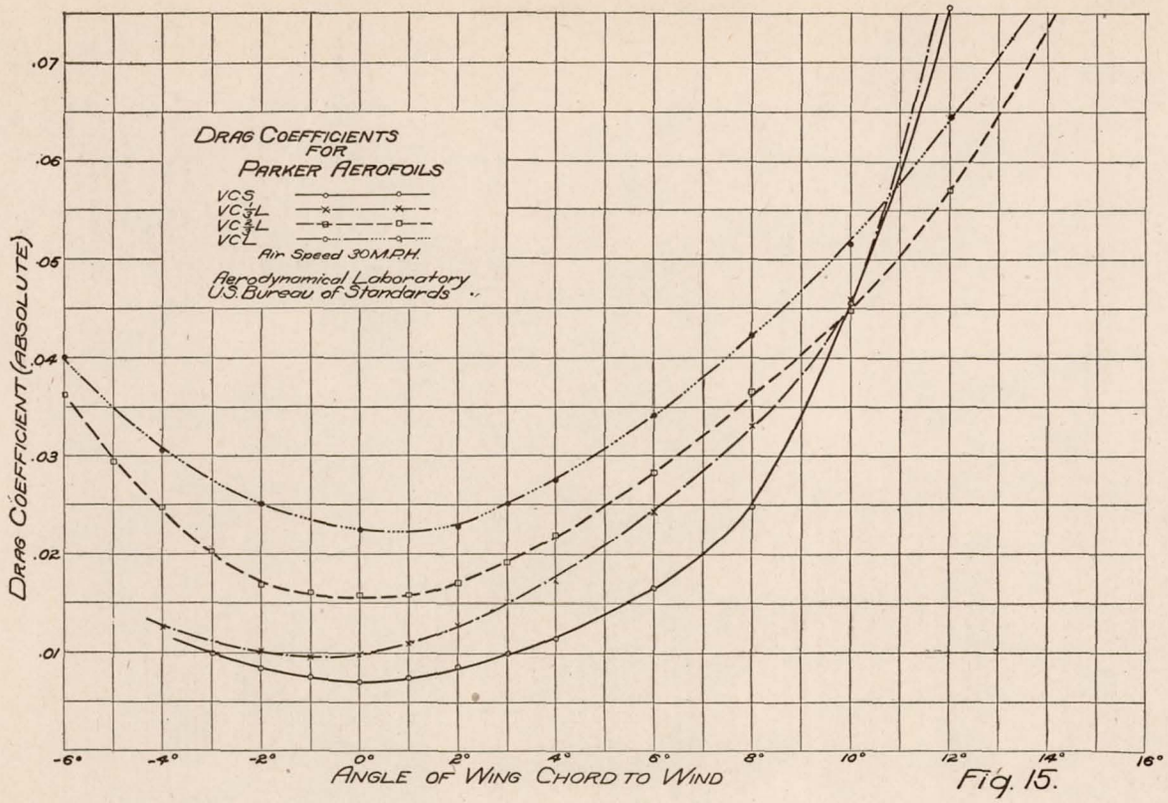


Fig. 15.

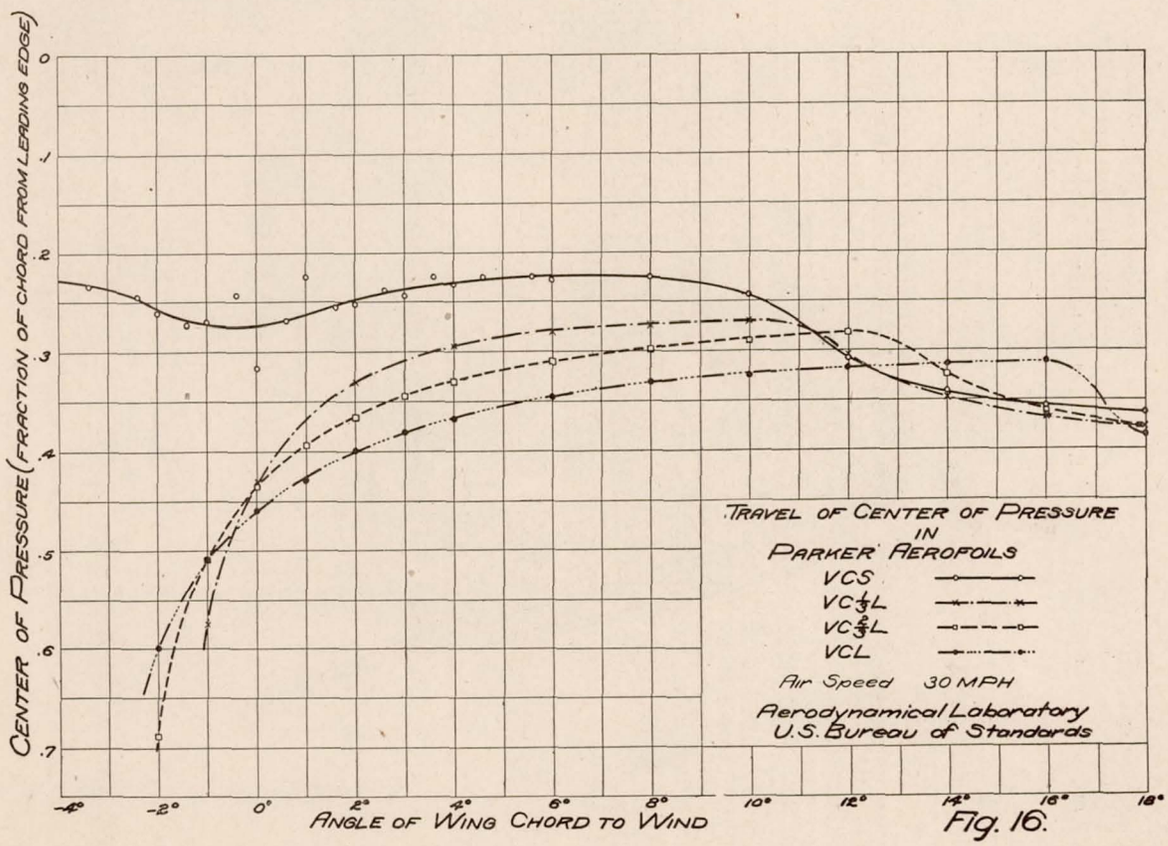


Fig. 16.

153215—S. Doc. 166, 66-2——52

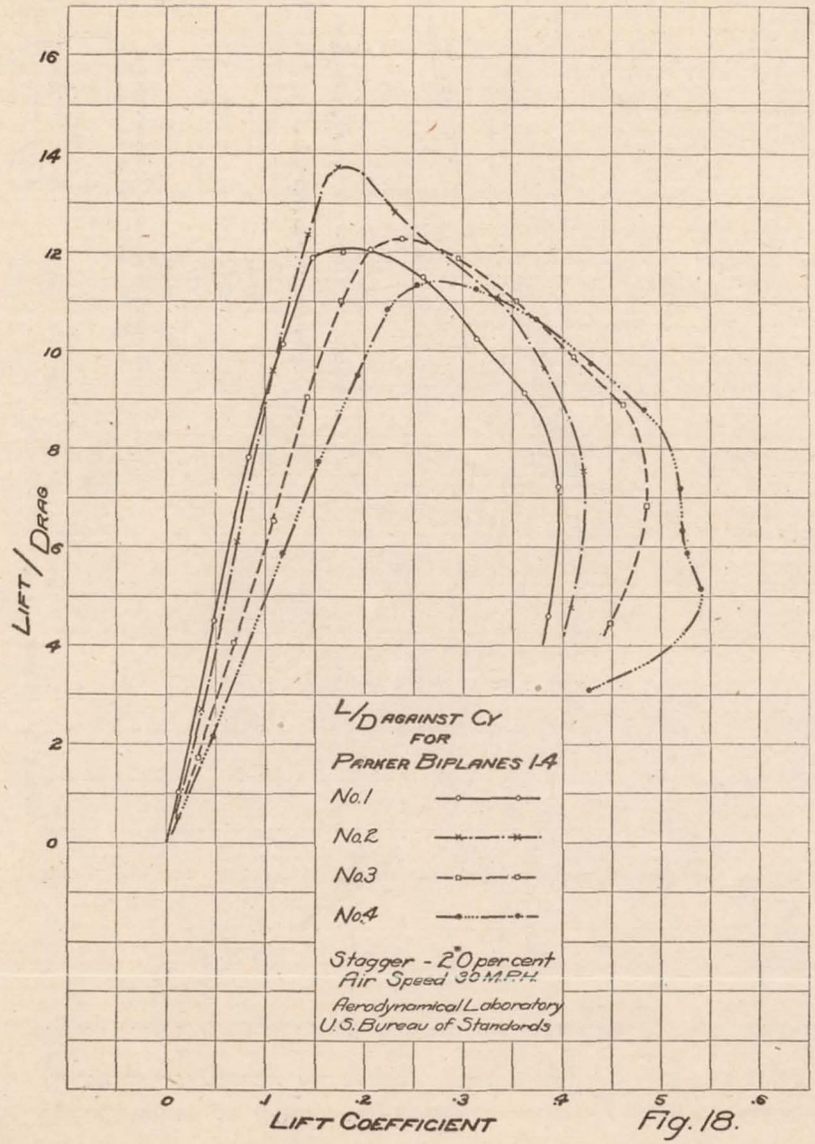

LIFT / DRAG
LIFT COEFFICIENT
L/D AGAINST CY
FOR
PARKER BIPLANES 1-4
No.1
No.2
No.3
No.4
Stagger - 20 per cent
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 18.

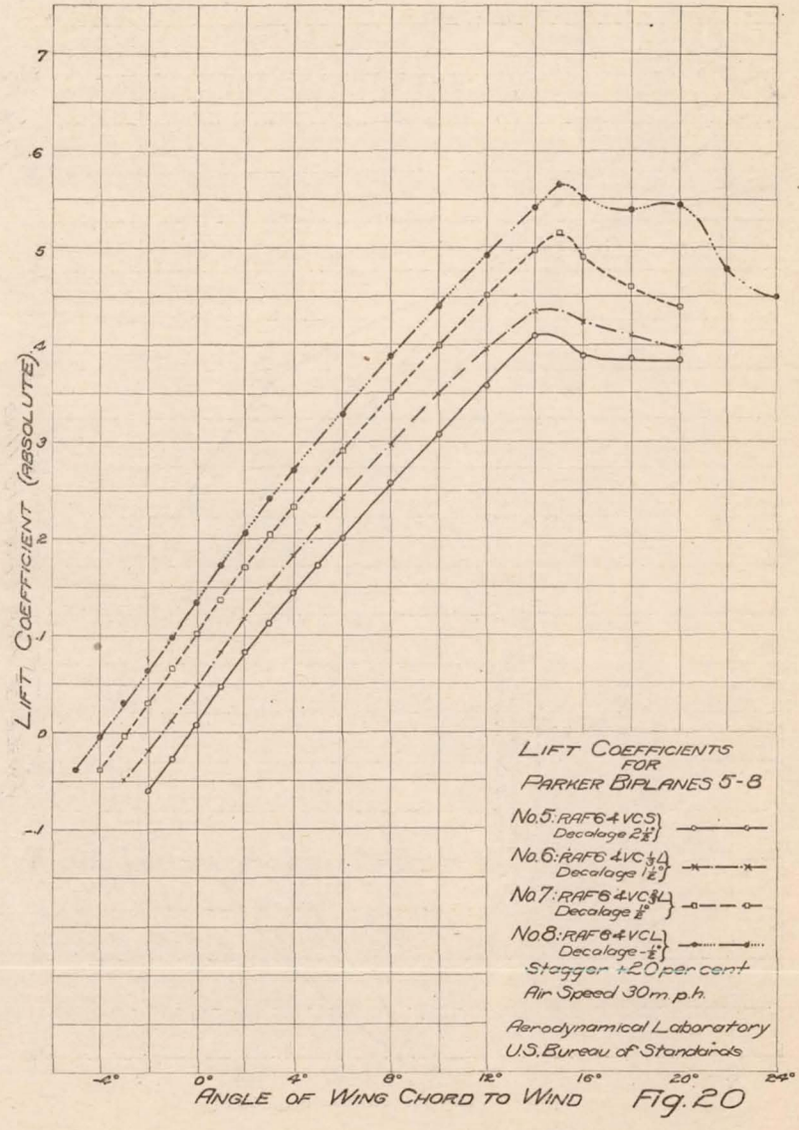

LIFT COEFFICIENT (ABSOLUTE)
ANGLE OF WING CHORD TO WIND
LIFT COEFFICIENTS
FOR
PARKER BIPLANES 5-8
No.5: RAF6 & VC5 Decalage 2°
No.6: RAF6 & VC5 1/2 Decalage 1°
No.7: RAF6 & VC5 1/2 Decalage 0°
No.8: RAF6 & VCL Decalage -1°
Stagger +20 per cent
Air Speed 30 m.p.h.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 20

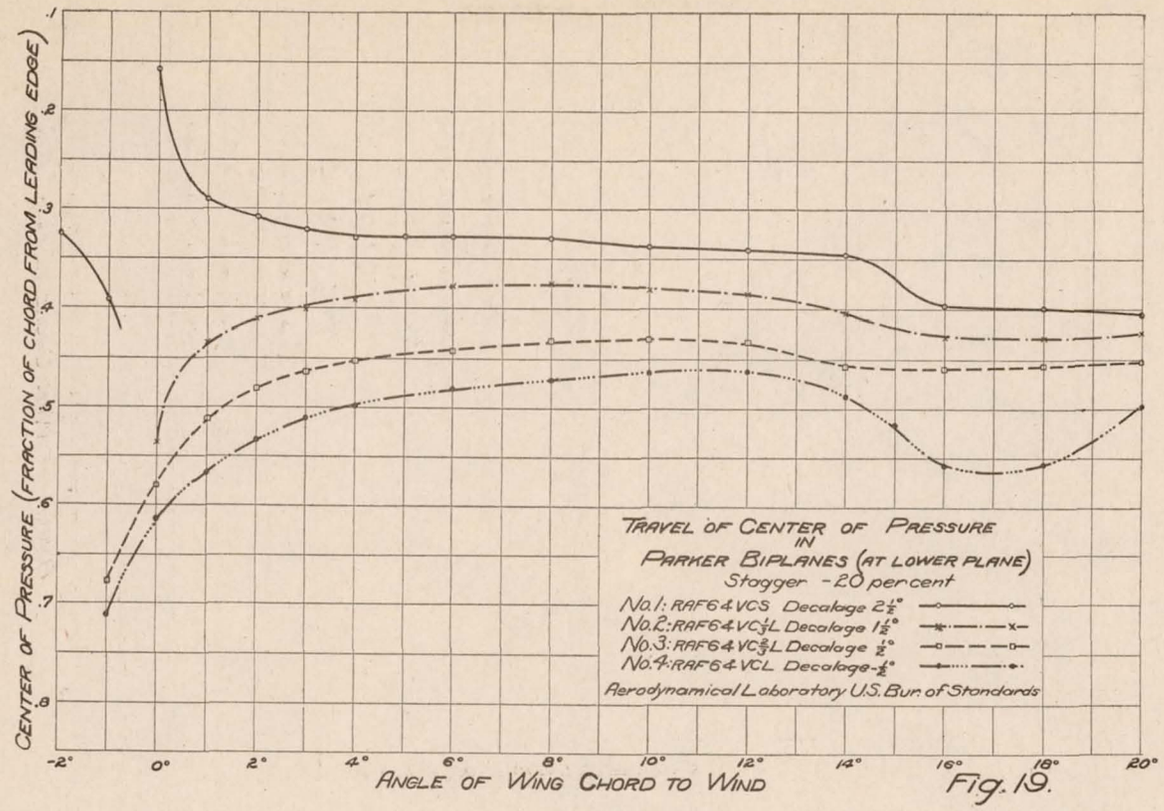

CENTER OF PRESSURE (FRACTION OF CHORD FROM LEADING EDGE)
.1
.2
.3
.4
.5
.6
.7
.8
-2°
0°
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
ANGLE OF WING CHORD TO WIND
TRAVEL OF CENTER OF PRESSURE
IN
PARKER BIPLANES (AT LOWER PLANE)
Stagger -20 per cent
No.1: RAF64 VCS Decalage 2½°
No.2: RAF64 VC½L Decalage 1½°
No.3: RAF64 VC⅝L Decalage ½°
No.4: RAF64 VCL Decalage -½°
Aerodynamical Laboratory U.S. Bur. of Standards

Fig. 19.

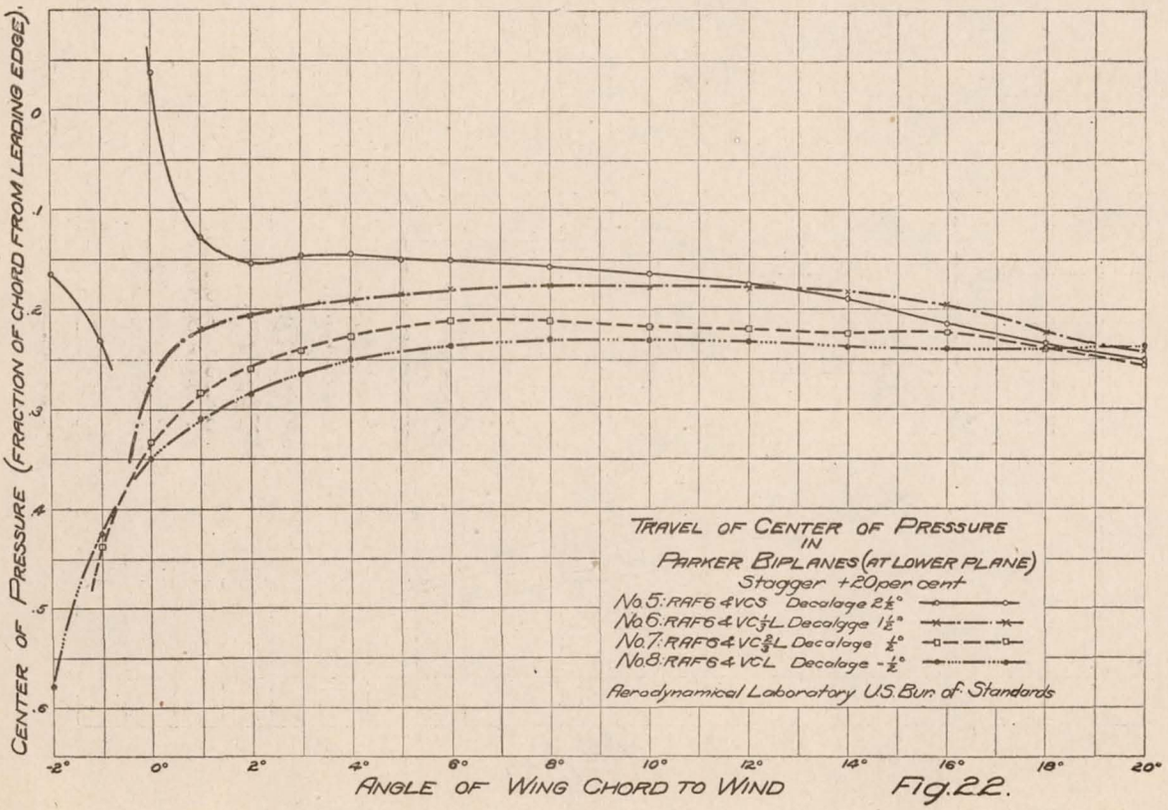

CENTER OF PRESSURE (FRACTION OF CHORD FROM LEADING EDGE)
0
.1
.2
.3
.4
.5
.6
-2°
0°
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
ANGLE OF WING CHORD TO WIND
TRAVEL OF CENTER OF PRESSURE
IN
PARKER BIPLANES (AT LOWER PLANE)
Stagger +20 per cent
No.5: RAF64 VCS Decalage 2½°
No.6: RAF64 VC½L Decalage 1½°
No.7: RAF64 VC⅝L Decalage ½°
No.8: RAF64 VCL Decalage -½°
Aerodynamical Laboratory U.S. Bur. of Standards

Fig. 22.

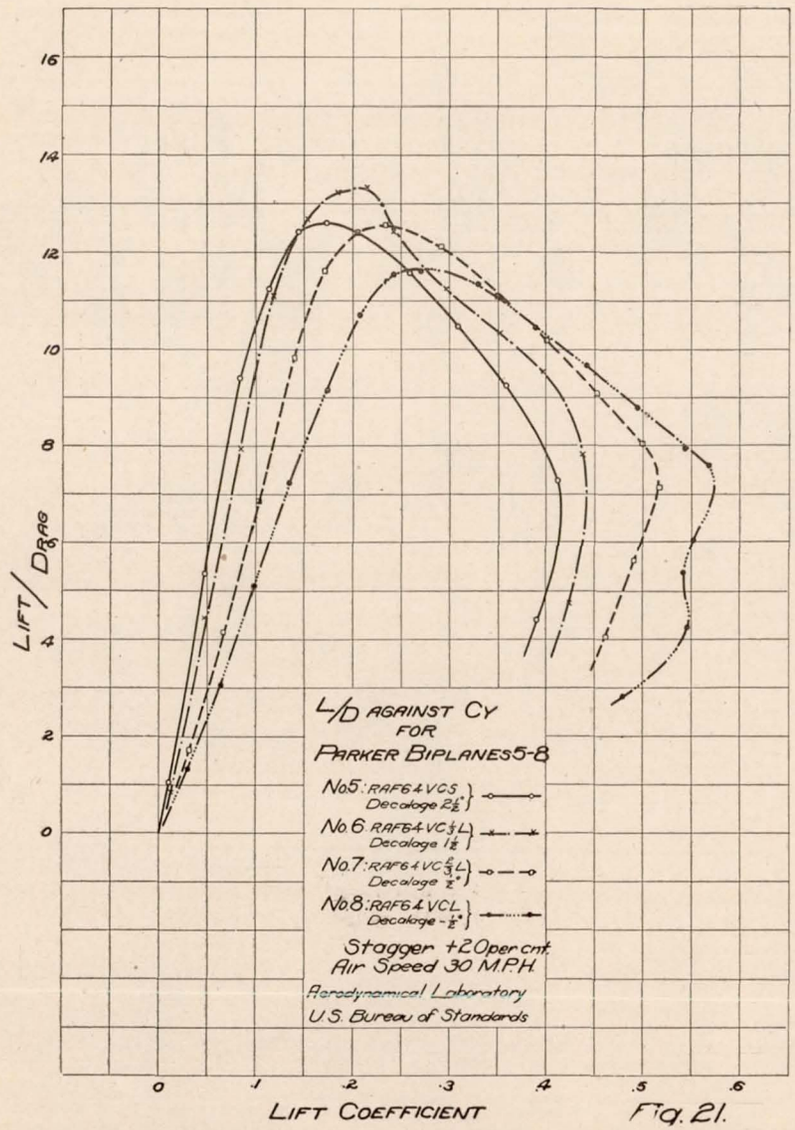

LIFT/DRAG
16
14
12
10
8
6
4
2
0
0
.1
.2
.3
.4
.5
.6
LIFT COEFFICIENT
L/D AGAINST CY
FOR
PARKER BIPLANES 5-8
No.5: RAF6 4 VCS Decalage 2½°
No.6: RAF6 4 VC½L Decalage 1½°
No.7: RAF6 4 VC½L Decalage ½°
No.8: RAF6 4 VCL Decalage -½°
Stagger +20 per cnt.
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 21.

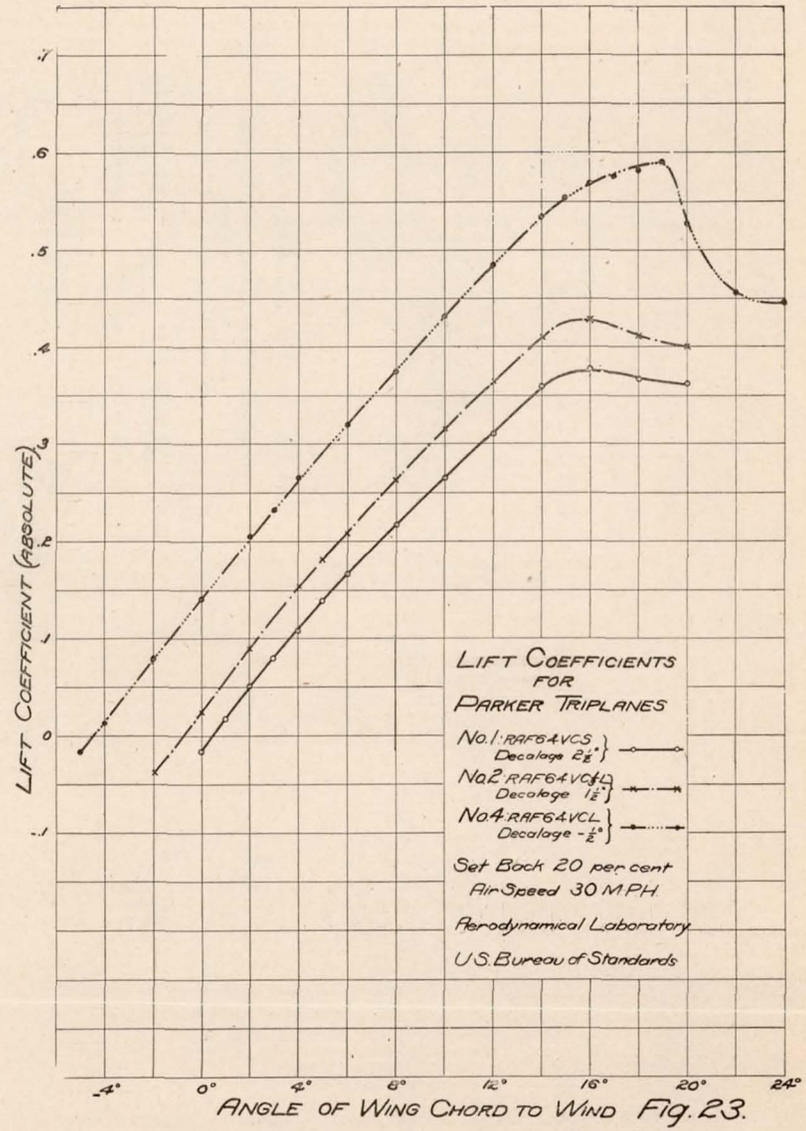

LIFT COEFFICIENT (ABSOLUTE)
.7
.6
.5
.4
.3
.2
.1
-4°
0°
4°
8°
12°
16°
20°
24°
ANGLE OF WING CHORD TO WIND
LIFT COEFFICIENTS
FOR
PARKER TRIPLANES
No.1: RAF6 4 VCS Decalage 2½°
No.2: RAF6 4 VC½L Decalage 1½°
No.4: RAF6 4 VCL Decalage -½°
Set Back 20 per cent
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 23.

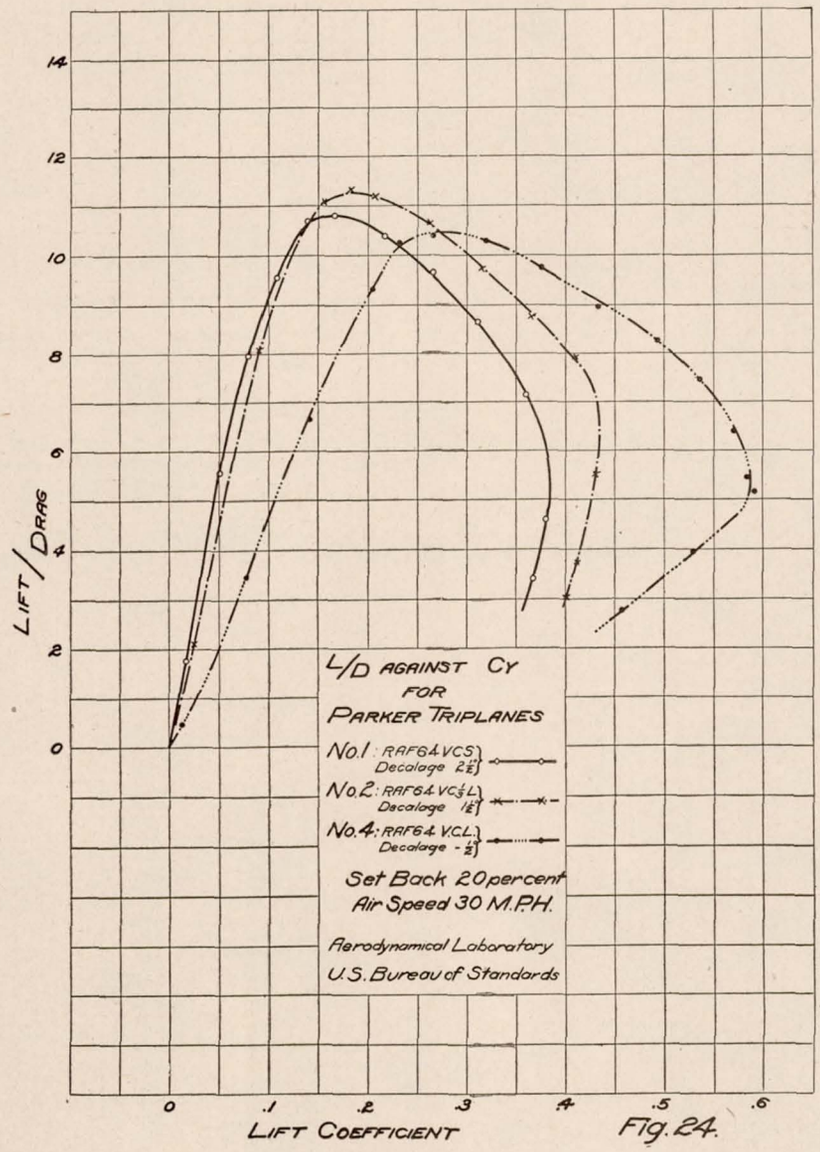

LIFT / DRAG
14
12
10
8
6
4
2
0
0
.1
.2
.3
.4
.5
.6
LIFT COEFFICIENT
L/D AGAINST Cy
FOR
PARKER TRIPLANES
No.1: RAF6&VCS } Decalage 2½°
No.2: RAF6&VC(½L) } Decalage 1°
No.4: RAF6&VCL } Decalage -½°
Set Back 20 percent
Air Speed 30 M.P.H.
Aerodynamical Laboratory
U.S. Bureau of Standards

Fig. 24.

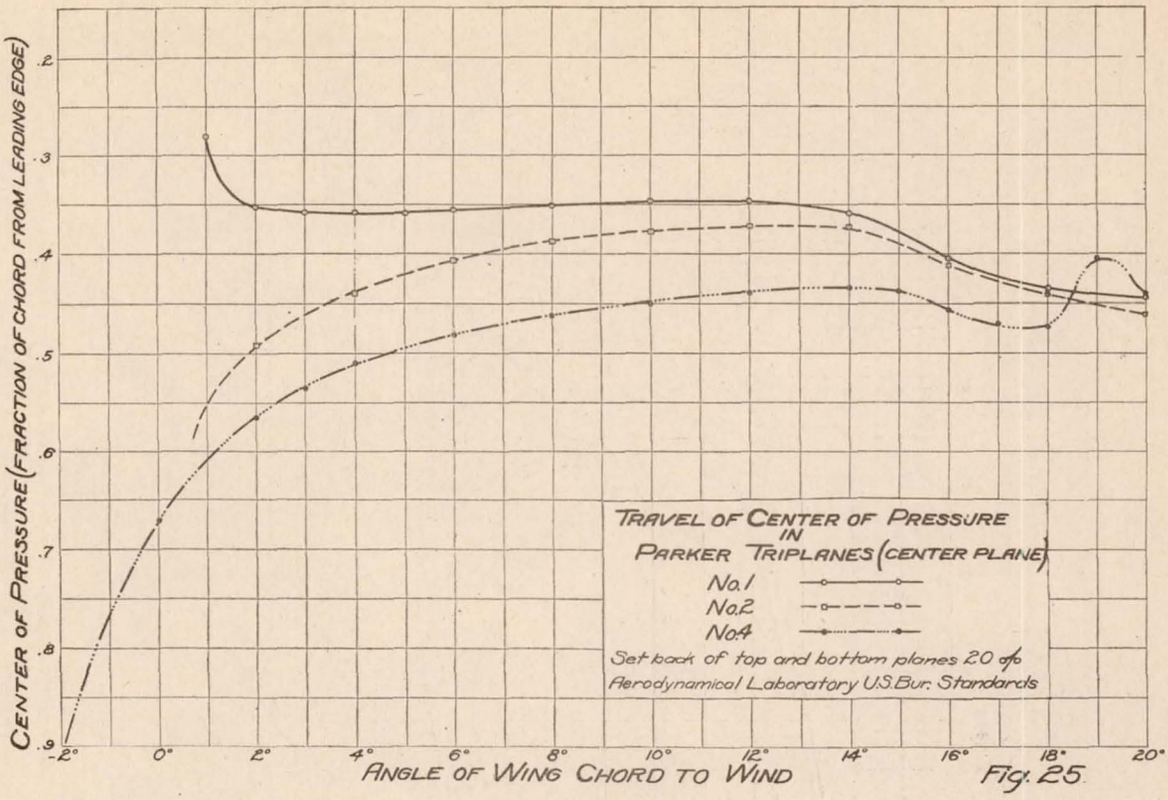


Fig. 25

APPENDIX.

Aerofoil, variable camber, stream-line, model (a).

Angle of attack (degrees).	Drag co-efficient (absolute).	Lift co-efficient (absolute).	Lift/drag.	Center of pressure co-efficient.
−6.4	0.0152	−0.2510	−16.58	0.224
−5.4	.0129	−.2124	−16.61	.226
−4.4	.0104	−.1759	−16.84	.225
−3.4	.0088	−.1398	−15.96	.234
−2.4	.0078	−.1039	−13.23	.244
−1.4	.0065	−.0637	− 9.85	.272
− .4	.0060	−.0183	− 3.06	.242
.6	.0066	.0290	4.39	.269
1.6	.0075	.0724	9.74	.255
2.6	.0091	.1090	12.06	.238
3.6	.0104	.1436	13.80	.225
4.6	.0127	.1810	14.20	.225
5.6	.0150	.2178	14.50	.225

Model:
- Chord..... 3 inches.
- Span..... 18 inches.
- Material..... Bakelite, paper base.

Air speed..... 40 miles per hour.

Center of pressure coefficient..... Distance of center of pressure from leading edge, in fractional part of chord.

Reference line..... Angle of no lift.

(Not plotted.)

Aerofoil, variable camber, stream-line model (b).

Angle of attack (degrees).	Drag co-efficient (absolute).	Lift co-efficient (absolute).	Lift/drag.	Center of pressure co-efficient.
− 3	0.0099	−0.1236	−12.48	0.286
− 2	.0084	− .0886	−10.55	.261
− 1	.0074	− .0433	− 5.85	.269
0	.0070	− .0025	− .36	.316
1	.0074	.0352	4.76	.224
2	.0087	.0822	9.45	.252
3	.0100	.1183	11.80	.244
4	.0114	.1540	13.50	.232
6	0165	.2230	13.50	.228
8	0248	.2920	11.80	.225
10	.0456	.3420	7.50	.243
12	.0760	.3630	4.78	.307
14	.0980	.3580	3.66	.341
16	.1160	.3550	3.06	.356
18	.1330	3530	2.66	.363
20	.1490	.3550	2.38	.366

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Bakelite, cloth base.
Air speed.....30 miles per hour.
Center of pressure coefficient.....Distance of center of pressure from leading edge, in fractional part of chord.
Reference line.....Center line of section of aerofoil.

Aerofoil, variable camber, one-third lifting model (a).

Angle of attack (degrees).	Drag co-efficient (absolute).	Lift co-efficient (absolute).	Lift/drag.	Center of pressure coefficient.
− 4	0.0114	−0.0766	− 6.74	−0.050
− 3	.0097	− .0424	− 4.37	− .076
− 2	.0091	− .0002	− .25	−4.930
− 1	.0087	.0450	5.20	.575
0	.0084	.0916	10.91	.417
1	.0096	.1341	14.00	....
2	.0113	.1721	15.18	.329
4	.0161	.2560	15.26	.294
6	.0218	.3182	14.56	.280
8	.0303	.3898	12.87	.273
10	.0412	.4540	11.01	.270
12	.0762	.4528	5.94	.307
14	.1033	.4266	4.13	.347
16	.1255	.4110	3.27	.368
18	.1461	.4120	2.82	.377
20	.1670	.4134	2.47	.383

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Bakelite, paper base.
Air speed.....40 miles per hour.
Reference line.....Tangent to lower surface at trailing edge.

(Not plotted.)

Aerofoil, variable camber, one-third lifting model (a).

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.
− 5	0. 0156	−0 1103	− 7. 09
− 4	. 0126	− . 0737	− 5 85
− 2	. 0102	− . 0034	− . 34
− 1	. 0096	. 0412	4 30
0	. 0099	. 0925	9. 32
1	. 0111	. 1378	12 44
2	. 0129	. 1752	13. 54
3	. 0153	. 2140	13. 97
4	. 0173	. 2474	14. 30
6	. 0243	. 3218	13. 25
8	. 0330	3932	11. 91
10	. 0456	. 4556	9. 99
12	. 0829	. 4468	5. 39
14	. 1069	. 4140	3. 87
16	. 1290	. 4080	3. 16
18	. 1487	. 4090	2. 75
20	. 1680	. 4100	2. 44

Model:
Chord ..... 3 inches.
Span ..... 18 inches.
Material ..... Bakelite, paper base.
Air speed ..... 30 miles per hour.
Reference line ..... Datum line of template.

Aerofoil, variable camber, one-third lifting model (b).

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.
− 6	0. 0187	−0. 1159	− 6. 20
− 4	. 0127	− . 0463	− 3. 64
− 2	. 0102	. 0278	2. 73
0	. 0107	. 1246	11. 67
2	. 0145	. 2018	13. 90
3	. 0165	. 2366	14. 35
4	. 0190	. 2740	14. 40
6	. 0268	. 3510	13. 08
8	. 0356	. 4198	11. 76
10	. 0481	. 4810	10. 00
12	. 0874	. 4582	5. 24
14	. 1094	. 4290	3. 92
16	. 1324	. 4158	3. 14
18	. 1509	. 4122	2 73
20	. 1715	. 4108	2. 39

Model:
Chord ..... 3 inches.
Span ..... 18 inches.
Material ..... Bakelite, cloth base.
Air speed ..... 30 miles per hour.
Reference line ..... Tangent to lower surface at trailing edge.
(Not plotted.)

Aerofoil, variable camber, two-thirds lifting.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−6	0.0362	−0.1243	−3.44	+0.174
−5	.0295	−.0850	−2.88	.061
−4	.0248	−.0352	−1.42	−.377
−3	.0202	.0206	1.02	+1.661
−2	.0168	.0701	4.18	.689
−1	.0160	.1177	7.35	.509
0	.0157	.1544	9.84	.435
1	.0158	.1925	12.19	.393
2	.0169	.2282	13.52	.366
3	.0190	.2684	14.21	.344
4	.0220	.3041	13.82	.330
6	.0282	.3792	13.43	.309
8	.0364	.4505	12.38	.297
10	.0448	.5110	11.40	.289
12	.0571	.5610	9.82	.281
14	.0978	.4975	5.09	.324
16	.1254	.4455	3.56	.360
18	.1420	.4270	3.01	.377
20	.1619	.4185	2.58	.382

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Bakelite, cloth base.
Air speed.....30 miles per hour.
Reference line.....Common tangent to lower surface.

Aerofoil, variable camber, lifting model (a).

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−7	0.0425	−0.1114	−2.62	0.240
−6	.0373	−.0706	−1.89	.071
−5	.0321	−.0212	−.66	−.782
−4	.0285	.0288	1.01	1.497
−3	.0251	.0740	2.95	.790
−2	.0236	.1194	5.07	.599
−1	.0229	.1637	7.16	.511
0	.0228	.2028	8.92	.460
1	.0232	.2432	10.48	.429
2	.0240	.2826	11.77	.398
3	.0262	.3200	12.20	.381
4	.0284	.3588	12.62	.367
6	.0349	.4324	12.40	.345
8	.0430	.5100	11.88	.331
10	.0528	.5780	10.95	.324
12	.0636	.6415	10.10	.317
14	.0768	.6965	9.07	.314
16	.0901	.7325	8.13	.311
17	.1363	.4985	3.66	....
18	.1467	.4765	3.25	.386
20	.1665	.4650	2.79	.392

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Bakelite, cloth base.
Air speed.....30 miles per hour.
Reference line.....Common tangent to lower surface.
(Not plotted.)

Aerofoil, variable camber, lifting model (b).

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.
−8	0.0511	−0.1275	−2.49
−6	.0400	−.0729	−1.82
−4	.0305	.0300	.98
−2	.0251	.1263	5.04
0	.0225	.2135	9.48
2	.0228	.2930	12.84
3	.0251	.3330	13.25
4	.0275	.3738	13.59
6	.0341	.4525	13.28
8	.0421	.5265	12.50
10	.0514	.5945	11.57
12	.0645	.6690	10.37
14	.0770	.7190	9.34
16	.0927	.7610	8.21
17	.1371	.5190	3.78
18	.1486	.5000	3.36

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Bakelite, cloth base.
Air speed.....30 miles per hour.
Reference line.....Common tangent to lower surface.

Aerofoil R. A. F. 6.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.
−4	0.0266	−0.0865	−3.25
−3	.0220	−.0455	−2.07
−2	.0181	−.0016	−.87
−1	.0159	.0407	2.56
0	.0148	.0900	6.10
1	.0138	.1453	10.51
2	.0141	.1927	13.66
3	.0158	.2316	14.67
4	.0178	.2656	14.91
6	.0241	.3316	13.73
8	.0326	.4042	12.41
10	.0421	.4650	11.05
12	.0534	.5220	9.78
14	.0848	.4910	5.79
16	.1080	.4360	4.04
18	.1297	.4242	3.27
20	.1457	.4274	2.94
22	.1656	.4258	2.57
24	.1886	.4232	2.24

Model:
Chord.....3 inches.
Span.....18 inches.
Material.....Wood.
Air speed.....30 miles per hour.
Reference line.....Common tangent to lower surface.
(Not plotted.)

Parker biplane No. 1.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−2	0.0146	−0.0587	−4.02	0.325
−1	.0132	− .0253	−1.92	.392
0	.0118	.0122	1.03	.165
1	.0109	.0490	4.50	.290
2	.0107	.0837	7.82	.309
3	.0116	.1174	10.12	.320
4	.0125	.1485	11.89	.329
5	.0149	.1788	12.00	.327
6	.0170	.2056	12.09	.328
8	.0226	.2596	11.50	.329
10	.0305	.3130	10.27	.337
12	.0395	.3615	9.14	.341
14	.0546	.3965	7.26	.346
16	.0840	.3875	4.61	.396
18	.1100	.3710	3.37	.399
20	.1272	.3615	2.84	.405

Upper plane.....V. C. S.
Lower plane.....R. A. F. 6.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent negative.
Decalage.....Upper plane set at 2½° less incidence than lower.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6, lower plane.
Center of pressure.....At chord of lower plane.

Parker biplane No. 2.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−2	0.0158	−0.0334	−2.12	0.052
−1	.0136	− .0010	− .07	−6.300
0	.0126	.0344	2.73	.536
1	.0115	.0705	6.13	.435
2	.0109	.1051	9.65	.412
3	.0115	.1423	12.37	.403
4	.0125	.1720	13.78	.393
6	.0179	.2295	12.82	.378
8	.0234	.2800	12.00	.375
10	.0304	.3380	11.11	.381
12	.0395	.3810	9.65	.385
14	.0556	.4200	7.55	.405
16	.0855	.4080	4.77	.428
18	.1061	.3860	3.64	.427
20	.1259	.3670	2.92	.424

Upper plane.....V. C. one-third lifting.
Lower plane.....R. A. F. 6.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent negative.
Decalage.....Upper plane set at 1½° less incidence than lower.
Air speed.....30 miles per hour.
Reference line.....Chord of lower plane R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 3.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−4	0.0251	−0.0495	−1.97	+0.107
−3	.0212	− .0090	− .42	−1.276
−2	.0186	.0312	1.68	+ .990
−1	.0169	.0686	4.05	.653
0	.0165	.1075	6.52	.555
1	.0158	.1427	9.06	.512
2	.0160	.1764	11.01	.481
3	.0173	.2073	12.01	.463
4	.0194	.2380	12.29	.452
6	.0248	.2944	11.85	.437
8	.0321	.3530	10.99	.432
10	.0415	.4090	9.86	.430
12	.0520	.4615	8.88	.433
14	.0709	.4845	6.84	.458
16	.1005	.4485	4.46	.460
18	.1226	.4230	3.45	.457
20	.1412	.4025	2.85	.453

Upper plane.....V. C. two-thirds lifting.
Lower plane.....R. A. F. 6.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent negative.
Decalage.....Upper plane set at ½° less incidence than lower.
Air speed.....30 miles per hour.
Reference line.....Chord of lower plane, R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 4.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−5	0.0331	−0.0652	−1.97	0.159
−4	.0284	− .0275	− .97	− .360
−3	.0247	.0116	.47	2.824
−2	.0221	.0472	2.14	.952
−1	.0205	.0820	4.00	.712
0	.0198	.1163	5.87	.614
1	.0197	.1531	7.76	.567
2	.0200	.1903	9.52	.534
3	.0206	.2234	10.84	.511
4	.0224	.2536	11.35	.498
6	.0278	.3136	11.27	.481
8	.0350	.3720	10.63	.472
10	.0440	.4275	9.73	.464
12	.0547	.4820	8.81	.463
14	.0722	.5180	7.19	.489
15	.0823	.5205	6.32	.517
16	.0898	.5275	5.87	.534
18	.1051	.5395	5.14	.557
20	.1391	.4255	3.06	.498
22	.1578	.4120	2.61	.491

Upper plane.....V. C. L.
Lower plane.....R. A. F. 6.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent negative.
Decalage.....Upper plane set at ½° greater incidence than lower.
Air speed.....30 miles per hour.
Reference line.....Chord of lower plane, R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 5.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−2	0.0124	−0.0601	−4.85	0.164
−1	.0109	−.0274	−2.50	.231
0	.0094	.0097	1.04	−.039
1	.0089	.0478	5.36	.127
2	.0089	.0840	9.41	.153
3	.0101	.1133	11.27	.145
4	.0118	.1442	12.21	.144
5	.0138	.1735	12.60	.150
6	.0163	.2014	12.33	.151
8	.0223	.2580	11.58	.158
10	.0294	.3080	10.48	.164
12	.0388	.3580	9.23	.175
14	.0564	.4110	7.29	.189
16	.0886	.3900	4.40	.214
18	.1127	.3870	3.44	.233
20	.1328	.3860	2.91	.250

Upper plane.....R. A. F. 6.
Lower plane.....V. C. S.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent positive.
Decalage.....Lower plane set at 2½° less incidence than upper.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 6.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−3	0.0161	−0.0497	−3.10	−0.021
−2	.0138	−.0198	−1.44	−.207
−1	.0124	.0107	.86	.725
0	.0108	.0481	4.45	.275
1	.0106	.0841	7.96	.219
2	.0107	.1153	11.10	.206
3	.0121	.1530	12.67	.198
4	.0140	.1845	13.22	.192
5	.0160	.2130	13.34	.184
6	.0195	.2420	12.41	.179
8	.0264	.2964	11.24	.176
10	.0340	.3510	10.33	.179
12	.0437	.3955	9.05	.180
14	.0558	.4355	7.81	.182
16	.0887	.4230	4.77	.194
18	.1150	.4105	3.57	.223
20	.1333	.3980	2.99	.242

Upper plane.....R. A. F. 6.
Lower plane.....V. C. one-third lifting.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent positive.
Decalage.....Lower plane set at 1½° less incidence than upper.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 7.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−4	0.0242	−0.0391	−1.61	−0.277
−3	.0207	−.0035	−.17	−4.070
−2	.0182	.0310	1.70	.757
−1	.0160	.0662	4.13	.437
0	.0149	.1022	6.85	.333
1	.0141	.1385	9.81	.283
2	.0147	.1711	11.61	.260
3	.0164	.2041	12.41	.241
4	.0185	.2330	12.55	.226
6	.0241	.2912	12.11	.211
8	.0314	.3464	11.03	.211
10	.0393	.4005	10.19	.217
12	.0498	.4520	9.08	.218
14	.0620	.4980	8.04	.224
15	.0726	.5160	7.11	.224
16	.0872	.4910	5.63	.222
18	.1142	.4610	4.04	.239
20	.1455	.4400	3.04	.256

Upper plane.....R. A. F. 6.
Lower plane.....V. C. two-thirds lifting.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent positive.
Decalage.....Lower plane set at ½° less incidence than upper.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker biplane No. 8.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−5	0.0293	−0.0385	−1.32	−0.407
−4	.0258	−.0046	−.18	−3.820
−3	.0231	.0305	1.32	1.070
−2	.0210	.0640	3.04	.579
−1	.0193	.0983	5.10	.425
0	.0186	.1347	7.23	.350
1	.0189	.1730	9.14	.309
2	.0193	.2063	10.70	.285
3	.0209	.2409	11.54	.265
4	.0233	.2701	11.60	.250
6	.0290	.3290	11.33	.237
8	.0371	.3880	10.46	.230
10	.0458	.4410	9.64	.231
12	.0562	.4930	8.80	.233
14	.0684	.5420	7.94	.237
15	.0747	.5660	7.57	.242
16	.0914	.5510	6.03	.240
18	.1100	.5390	4.91	.239
20	.1280	.5450	4.26	.238
22	.1880	.4780	2.83	.276
24	.1915	.4500	2.35	.280

Upper plane.....R. A. F. 6.
Lower plane.....V. C. L.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....20 per cent positive.
Decalage.....Lower plane set at ½° greater incidence than upper.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of lower plane.

Parker triplane No. 1.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
0	0.0099	−0.0163	−1.64	0.469
1	.0091	.0162	1.78	.281
2	.0090	.0506	5.59	.352
3	.0100	.0796	7.97	.358
4	.0113	.1080	9.58	.359
5	.0129	.1392	10.70	.361
6	.0154	.1660	10.78	.356
8	.0209	.2172	10.38	.351
10	.0275	.2656	9.67	.347
12	.0361	.3115	8.64	.348
14	.0504	.3600	7.14	.360
16	.0824	.3785	4.60	.405
18	.1032	.3675	3.39	.435
20	.1265	.3630	2.87	.445

Top plane.....V. C. S.
Middle plane.....R. A. F. 6.
Bottom plane.....V. C. S.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....Top and bottom planes set 20 per cent of chord behind middle plane.
Decalage.....Top and bottom planes set at 2½° less incidence than middle plane.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of middle plane.

Parker triplane No. 2.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−2	0.0146	−0.0353	−2.42	−0.049
0	.0118	.0243	2.05	.870
2	.0110	.0885	8.09	.491
4	.0140	.1553	11.10	.438
5	.0161	.1829	11.34	.422
6	.0186	.2076	11.19	.406
8	.0246	.2620	10.63	.387
10	.0325	.3100	9.72	.378
12	.0413	.3656	8.86	.372
14	.0518	.4102	7.92	.373
16	.0778	.4290	5.52	.411
18	.1108	.4128	3.73	.440
20	.1323	.4010	3.03	.461

Top plane.....V. C. one-third lifting.
Middle plane.....R. A. F. 6.
Bottom plane.....V. C. one-third lifting.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....Top and bottom planes set 20 per cent of chord behind middle plane.
Decalage.....Top and bottom planes set at 1½° less incidence than middle plane.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of middle plane.

Parker triplane No. 4.

Angle of attack (degrees).	Drag coefficient (absolute).	Lift coefficient (absolute).	Lift/drag.	Center of pressure coefficient.
−5	0.0310	−0.0218	−0.70	−1.191
−4	.0275	.0129	.47	4.208
−2	.0227	.0779	3.43	.927
0	.0212	.1414	6.68	.670
2	.0220	.2048	9.32	.566
3	.0228	.2324	10.27	.536
4	.0255	.2652	10.39	.510
6	.0312	.3205	10.30	.482
8	.0385	.3755	9.77	.462
10	.0483	.4330	8.96	.450
12	.0587	.4855	8.26	.440
14	.0716	.5345	7.47	.434
15	.0781	.5540	7.10	.437
16	.0893	.5695	6.38	.456
17	.0988	.5755	5.82	.470
18	.1064	.5825	5.48	.473
19	.1142	.5910	5.17	.404
20	.1332	.5275	3.96	.441
22	.1640	.4565	2.78	.478
24	.1870	.4465	2.39	.487

Top plane.....V. C. L.
Middle plane.....R. A. F. 6.
Bottom plane.....V. C. L.
Chord.....3 inches.
Span.....18 inches.
Gap.....3 inches.
Stagger.....Top and bottom planes set 20 per cent of chord behind middle plane.
Decalage.....Top and bottom planes set at ½° greater incidence than middle plane.
Air speed.....30 miles per hour.
Reference line.....Chord of R. A. F. 6.
Center of pressure.....At chord of middle plane.

Lift/drag against speed.

Parker biplane back stagger.		Parker biplane forward stagger.		R. A. F. 6 biplane.		Parker triplane.		R. A. F. 6 triplane.	
Speed.	Lift/drag.	Speed.	Lift/drag.	Speed.	Lift/drag.	Speed.	Lift/drag.	Speed.	Lift/drag.
3.32	5.55	3.440	7.05	3.58	2.30	3.42	7.30	3.58	2.10
2.54	9.75	2.600	12.38	2.42	5.22	2.73	10.10	2.42	5.05
2.25	12.33	2.240	14.24	1.90	9.20	2.34	11.80	1.90	8.80
1.95	15.13	1.920	15.40	1.65	12.00	1.95	13.15	1.65	11.25
1.77	16.51	1.750	15.60	1.50	13.20	1.80	13.10	1.50	12.40
1.35	13.00	1.630	15.40	1.40	13.90	1.69	12.60	1.50	12.90
1.24	11.80	1.390	13.20	1.26	12.80	1.25	10.28	1.26	11.70
1.15	10.40	1.280	11.84	1.14	10.90	1.17	9.35	1.14	10.70
1.06	8.50	1.190	10.80	1.06	10.35	1.10	8.60	1.06	9.90
1.02	7.40	1.070	9.13	1.00	9.70	1.05	7.70	1.00	9.10
1.00	5.24	1.025	8.18	.....	.....	1.02	6.55	.....	.....
.....	.....	1.000	7.80	.....	.....	1.00	5.26	.....	.....

Deflection of rib under overloads.

Load.		Deflection.					
		In inches, at distance from leading edge of—					
Number of flying loads.	Total load (pounds).	1½ inches (front spar).	12 inches (A).	21 inches (B).	30 inches (C).	39 inches (rear spar).	60 inches (trailing edge) (D).
1	33.5	0	0	0	0	0	0
2	67.0	0	.066	.081	.061	0	−.020
3	100.5	0	.092	.130	.111	0	−.050
4	134.0	0	.137	.178	.164	0	−.103
5	167.5	0	.186	.228	.199	0	−.105
6	201.0	0	.208	.260	.229	0	−.089
7	234.5	0	.244	.303	.266	0	−.095
8	268.0	0	.324	.349	.306	0	−.090
9	301.5	0	.354	.385	.342	0	−.093
10	335.0	0	.400	.437	.393	0	−.092
11	368.5	Rib failed by buckling of channel flanges.					

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REPORT No. 78

THE LIMITING VELOCITY IN FALLING FROM A GREAT HEIGHT.

BY EDWIN BIDWELL WILSON

Massachusetts Institute of Technology, Cambridge, Mass.

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REPORT No. 78.

THE LIMITING VELOCITY IN FALLING FROM A GREAT HEIGHT.

By Edwin Bidwell Wilson.

1. The fundamental characteristic of the vertical motion under gravity in a resisting medium is the approach to a final or limiting velocity U, whether the initial downward velocity is less or greater than U. The equations of motion are easily set up and integrated when the density of the medium is constant and the resistance varies as the square of the velocity.

A fact not so much stressed is the slowness of the approach to the limiting velocity U. For example the simple relation $v^2 = 2gh$, which neglects altogether the resistance of the atmosphere, shows t' at the height h of release from rest must be about 10,000 feet before the object will attain a velocity of as much as 800 ft./sec. even without the opposition of the air resistance; and when allowance is made for that resistance the height must be greater. If, therefore, terminal velocities of 900 or more feet per second, such as are customary with airplane bombs, are under consideration, it is only in the case of fall from a great height (upward of 10,000 feet) that the terminal velocity can be anywhere nearly approached.

Here, however, another difficulty enters. The resistance of the air varies with the density of the medium and this variation should not be assumed a priori to be negligible in the case of fall from heights of upward of 2 miles. In the standard table of densities at different levels, the ratio ρ/ρ_0 of the density at altitude h to that at the earth has become about 0.74 at 10,000 feet, 0.62 at 15,000, and 0.44 at 25,000. The question thus arises as to whether the changing resistance of the air may be taken into account in some satisfactorily simple way for the discussion of vertical fall.

It is the purpose of this report to give that simple treatment of the problem which I have in the past offered to my classes at the Massachusetts Institute of Technology; there are undoubtedly other solutions, perhaps equally simple or simpler, but I have seen none.

2. The equation of motion is

$$W\frac{dv}{dt} = -\,Wg + cg\rho(h)v^2$$

if W be the mass, v the velocity upward, and $c\rho v^2$ be the resisting force in pounds. With the substitution $u = v^2$ the equation reduces to $\dfrac{du}{dh} - \dfrac{2cg\rho}{W}u = -2g$ and is linear, but with a variable coefficient ρ. The general solution may be indicated in the form

$$ue^{-\frac{2cg}{W}\int \rho dh} = -2g\int e^{-\frac{2cg}{W}\int \rho dh}\,dh + C$$

In order to perform the integration it is necessary (unless graphical methods are used) to have an expression for ρ as a function of h that is sufficiently accurate and at the same time of such form as to make integrable the two expressions

$$\int \rho dh \quad \text{and} \int e^{-\frac{2cg}{W}\int \rho dh}\,dh + C$$

Some work will be saved if the first expression can itself be represented by an empirical equation directly without having first to determine ρ and then integrate that result.

3. Physically $\int_o^h \rho dh$ is the amount of air between the earth and the height h in a column of unit cross section. This amount can fortunately be read off immediately from a table of barometric pressures p at different levels—in fact $\int_o^h \rho dh$ is simply $p_0 - p_1$, the drop in pressure in pounds per square foot.

If $F(h)$ is the amount of air in inches of mercury, the following table gives the value of F from $h=0$ to $h=24{,}000$ feet.

$h=$	0	4,000	8,000	12,000	16,000	20,000	24,000
$F=$	0	4.07	7.68	10.85	13.62	16.02	18.09

Now, as the exponential of F (multiplied by a constant) must be integrated, it is advisable to have a logarithmic expression to give the empirical relation between h and F. Try:

$$F(h) = b \log_e (1 + ah).$$

This holds for $h=0$ and has two disposable constants a and b. A least-squares solution could be made to determine the best values for a and b; but a sufficiently good result may be had by passing the curve through or near two sets of values in the table:

$$F_1 = b \log (1 + a\, h_1), \quad F_2 = b \log (1 + a\, h_2):$$
$$F_1 : F_2 = \log (1 + a\, h_1) : \log (1 + a\, h_2), 1 + a\, h_1 = (1 + a\, h_2)^{F_1/F_2}$$

Let $h_2 = 8{,}000$. Then $F_2 = 7.68$. Let $F_1 = 2F_2 = 15.36$. Then h_1 is just under 20,000 and may be taken as $h_1 = 19{,}000$ by interpolation. Hence

$$1 + 19{,}000\, a = (1 + 8000\, a)^2 = 1 + 16{,}000\, a + 64{,}000{,}000\, a^2$$

and

$$a = 3/64{,}000. \quad \text{Whence } b = 24.1.$$

Thus

$$F(h) = 24.1 \log_e (1 + 3h/64{,}000) = 55.5 \log_{10} (1 + 3h/64{,}000).$$

The values determined by this function F are

$h=$	0	4,000	8,000	12,000	16,000	20,000	24,000
$F=$	0	4.05	7.68	10.8	13.5	15.9	18.1

These check with the given values to less than 1 per cent, and therefore seem quite good enough.

4. The empirical formula just obtained must be transformed over to suitable units for insertion in the integral of the differential equation. Let U be the terminal or limiting velocity of the projectile in air of the density ρ_u at the earth's surface. Then

$$cg\rho_0 U^2 = Wg \text{ or } c = W/U^2\rho_0$$
$$\frac{-2cg}{W}\int \rho dh = \frac{-2g}{\rho_0 U^2}\int \rho dh.$$

If the units be the pound and foot

$$\int_o^h \rho dh = \frac{13.6}{12} \times 62.5 \times F(h) = 1706 \log_e (1 + 3h/64{,}000).$$

Taking $g = 32.17$ and $\rho_0 = .07608$, the result is

$$\frac{-2g}{\rho_0 U^2}\int_o^h \rho dh = \frac{-1{,}430{,}000}{U^2} \log \left(1 + \frac{3h}{64{,}000}\right).$$

With an error of less than 1 per cent this may be written as

$$\frac{-2g}{\rho_0 U^2}\int_o^h \rho dh = -\left(\frac{1200}{U}\right)^2 \log \left(1 + \frac{3h}{64{,}000}\right).$$

An error of 1 per cent seems quite within the range of accuracy possible in such work as this, where the variation of atmospheric conditions from the so-called standard table may at any particular time be considerable.

The integral is therefore

$$v^2\left(1+\frac{3h}{64{,}000}\right)^{-\left(\frac{1200}{U}\right)^2}=-2g\int\left(1+\frac{3h}{64{,}000}\right)dh^{-\left(\frac{1200}{U}\right)^2}+C,$$

where the only parameter remaining is the terminal velocity U in air of standard density.

If in particular a particle starts from rest at the altitude H,

$$v^2\left(1+\frac{3h}{64{,}000}\right)^{-\left(\frac{1200}{U}\right)^2}=2g\int_h^H\left(1+\frac{3h}{64{,}000}\right)^{-\left(\frac{1200}{U}\right)^2}dh.$$

The integral may be evaluated readily, as the integrand is a simple negative power, but leads to a complicated literal formula.

A simple case would be where $U=1{,}200$. Then

$$v^2=2g\left(1+\frac{3h}{64{,}000}\right)\frac{64{,}000}{3}\log_e\left[\frac{1+\frac{3H}{64{,}000}}{1+\frac{3h}{64{,}000}}\right]$$

This is the only case in which a logarithm enters; the others are algebraic, e. g., if $U=600$,

$$v^2=2g\left(1+\frac{3h}{64{,}000}\right)^4\frac{64{,}000}{3\times3}\left[\left(1+\frac{3h}{64{,}000}\right)^{-3}-\left(1+\frac{3H}{64{,}000}\right)^{-3}\right]$$

5. The formulas thus obtained should not be applied to calculate velocities which are large compared with that of sound. It is generally admitted that the simple square law of resistance does not hold for velocities much in excess of 800 ft./sec. Just how well the law holds below that figure may still be considered doubtful; but two recent authorities (E. Vallier, Balistique Exterieure, Encyclopedie des Sciences Mathematiques, tome IV, Vol. 6, fasc. 1, p. 15, Gauthier–Villars, Paris, 1913; and J. Prescott, London, Phil. Mag., ser. 6, vol. xx, p. 332, Oct. 1917) seem to feel tolerably certain of the law for compact shell-like bodies up to 800 ft./sec. It was seen at the start that irrespective of air resistance, such a velocity would not be obtained from rest in a fall of 10,000 feet. If $U=1{,}200$, the velocity of 800 ft./sec. will be reached at the earth's surface only when the fall is through some 15,000 feet. (Whether high velocities might not be attained at intermediate levels is a question that should not be overlooked.)

6. It is often stated, as is indeed obvious, that a body falling in a medium of increasing density such as the air may reach a maximum velocity and be subsequently retarded before striking the earth. The terminal velocity toward which the body strives is of course greater at higher levels. The question of reaching a maximum velocity is therefore a question of balance between the height of fall and the natural resistance of the body relative to its weight. A body of high terminal velocity (in standard air) must fall from a very great height in order to attain a maximum greater than the speed with which it reaches the earth, whereas a body of low terminal velocity need not fall so far.

The maximum velocity of a body falling from rest is obtained by differentiating

$$v^2=2g\left(1+\frac{3h}{64,000}\right)^{\left(\frac{1200}{U}\right)^2}\int_h^H\left(1+\frac{3h}{64,000}\right)^{-\left(\frac{1200}{U}\right)^2}dh.$$

The derivative of an integral with respect to the lower limit is the negative of the integrand

Hence for the maximum of v, or of v^2

$$-1+\left(\frac{1,200}{U}\right)^2\left(1+\frac{3h}{64,000}\right)^{\left(\frac{1200}{U}\right)^2}-1\left[\frac{\left(1+\frac{3H}{64,000}\right)^{-\left(\frac{1200}{U}\right)^2+1}-\left(1+\frac{3h}{64,000}\right)^{-\left(\frac{1200}{U}\right)^2+1}}{-\left(\frac{1,200}{U}\right)^2+1}\right]=0$$

For a given H this equation will determine the level h where the maximum velocity is attained.

If in particular this maximum should be at $h=0$, the altitude H of fall must be

$$H=\frac{64,000}{3}\left[\left(\frac{1,200}{U}\right)^{\frac{2}{\left(\frac{1200}{U}\right)^2-1}}-1\right]$$

For example, if $U=600$, $H=12,500$. The maximum velocity will be reached before striking the earth only if $H>12,500$. If $U=1,200$, the bracket has the value $e-1=1.73$, and the maximum value will not be attained unless the drop is from over 35,000 feet—levels to which the empirical formulas used do not remain valid.

In any case of resisted fall in which a maximum of velocity is attained the value of that maximum velocity must be the value of the terminal velocity at that level, because the body has been gaining velocity in the rarer air above and will be losing velocity in the denser air below.

If, therefore, the velocity at $h=0$ is below the terminal velocity U, it may safely be assumed that the value for $h=0$ has not been exceeded; but if the value for $h=0$ is larger than U, there has been a still larger velocity at some point of the path. The caution parenthetically suggested at the end of the last article can therefore be observed easily.

Massachusetts Institute of Technology, *September 6, 1919.*

REPORT No. 79

BOMB TRAJECTORIES

By EDWIN BIDWELL WILSON

Massachusetts Institute of Technology, Cambridge, Mass.

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REPORT No. 79.

BOMB TRAJECTORIES.

By Edwin Bidwell Wilson.

I. INTRODUCTORY.

The trajectory of a bomb of high terminal velocity dropped from a great altitude such as 30,000 feet requires a complicated analysis much like that for the trajectory of a shell fired at a high angle. For, in the first place, the changing density of the air can not be wholly ignored, and in the second place, the air resistance as a function of the velocity is exceedingly complicated, and, in particular, as the bomb may pass through the velocity of sound in air, all sorts of complications leading even to instability and tumbling, which render any calculation of the trajectory illusory, may be present.

I have pointed out in a previous note on the Limiting Velocity of Free Fall that bombs of high terminal velocity must fall over 10,000 feet and acquire a velocity of 800 ft./sec., that bombs of lower terminal velocity must fall through even greater distances, and that there is tolerable agreement among ballisticians that up to velocities of about 800 ft./sec., the simple square law of resistance ($R \propto v^2$) holds for solid shell-like bodies. The problem which I wish to treat here is that of the trajectory of a bomb launched horizontally when the fall is not so great that the velocity exceeds 800 ft./sec., at any point of the path. Only the first approximation founded on the assumption of constant air density will be developed.

II. GENERAL CONSIDERATIONS.

This problem has been treated in several ways in an elementary manner, e. g., by E. L. Gayhart in "Aviation," Volume III, No. 12, January 15, 1918, pages 819–822, after the German, by Ernest Hemkel. My discussion, likewise elementary, is that which I have given students of aeronautical engineering at the Massachusetts Institute of Technology, and which may be of interest to others.

If V be the velocity in path, u, v the component velocities horizontal and vertical downward, respectively, U the terminal velocity, the resistance is $R = kV^2 = WV^2/U^2$ pounds, where W is the mass. The equations of motion are

$$\frac{du}{dt} = -g\frac{uV}{U^2}, \qquad \frac{dv}{dt} = g\left(1 - \frac{vV}{U^2}\right) \tag{1}$$

or

$$\frac{V^2}{r} = g\frac{u}{V}, \qquad \frac{dV}{dt} = g\left(\frac{v}{V} - \frac{V^2}{U^2}\right), \tag{2}$$

according as the motion is referred to rectangular axes or to the tangent and normal to the path (radius of curvature $= r$).

The second of (2) may be written

$$V\frac{dV}{dy} = g\left(1 - \frac{V^2}{U^2}\frac{V}{v}\right),$$

and compared with the equation for vertical fall in which $V = v$. For the trajectory V/v is always greater than unity and hence the increase of V with the vertical drop y is always less than the increase of v with vertical drop y when the fall is itself vertical. In other words, in

the trajectory the bomb gains tangential velocity with vertical drop more slowly than vertical velocity is gained in free fall.

Now bombs are released with a horizontal velocity $V_0 = u_0$ which is small relative to their terminal velocity U. Even a fast-moving airplane will hardly exceed 200 ft./sec., and a bomb with low terminal velocity will have U probably not less than 800 ft./sec., so that u_0/U is almost sure not to exceed 1/4. In the case of free fall

$$\frac{2gh}{U^2} = \log_e\left(1-\frac{v_0^2}{U^2}\right) - \log_e\left(1-\frac{v^2}{U^2}\right)$$

and the distance h of fall required to reach a velocity of v from rest exceeds that required to reach the same velocity from an initial vertical velocity of $v_0 = U/4$ by only the amount

$$\Delta h = \frac{-U^2}{2g}\log_e\left(1-\frac{1}{16}\right) = \frac{U^2}{32g} = \left(\frac{U}{g}\right)^2, \text{ approx.}$$

If U be 800 ft./sec., the additional distance is only 625 feet.

It may therefore be stated that a bomb launched horizontally with a velocity as high as 200 ft./sec. and with a terminal velocity as low as 800 ft./sec. will require, to attain a linear (tangential) velocity of V, a vertical drop of less than 625 feet less than that required by a body falling from rest. (If v_0/U is, as it generally is, decidedly smaller than 1/4, the distance 625 feet is very much reduced.)

The reasoning shows that for all practical purposes one may consider that a velocity on a trajectory will remain under 800 ft./sec. even though the initial velocity be high, provided the vertical drop is not so large as to generate a vertical velocity in excess of 800 ft./sec in the case of free fall. This brings the safety limit for the application of the square law for resistance back practically to the case of the previous note.

The relation between the arc s described on the trajectory and the velocity acquired may be discussed from the second of (2).

For

$$V\frac{dV}{ds} = g\left(\frac{v}{V} - \frac{V^2}{U^2}\right)$$

may be compared with

$$v\frac{dv}{dy} = g\left(1-\frac{v^2}{U^2}\right)$$

to see that tangential velocity V is gained along the trajectory relative to the distance traveled. s, much more slowly than vertical velocity is gained relative to y in the case of straight fall, the term v/V being always less than 1. In fact, at the start, tangential velocity is lost, since $v/V = 0$.

III. PRELIMINARY INTEGRATION.

With reference to the arc s of the trajectory the first equation of (1) may be integrated. Thus—

$$\frac{du}{dt} = \frac{du}{ds}\frac{ds}{dt} = V\frac{du}{ds}, \qquad \frac{du}{ds} = -\frac{gu}{U^2}, \qquad u = u_0 e^{-gs/U^2}. \tag{3}$$

The horizontal velocity falls off exponentially with the arc traveled. For example, if $U = 800$, $g/U^2 = 1/20{,}000$; the horizontal velocity will be reduced 1/2 only after a travel of 14,000 feet. Now if the time to be eliminated between the two equations (1) to obtain the differential equation of the trajectory, or, better, if the first equation of (2) be used for this purpose, it is seen that

$$\frac{d^2y}{dx^2} = \frac{g}{u^2} = \frac{g}{u_0^2}e^{2gs/U^2}. \tag{4}$$

For

$$\frac{1}{r} = \frac{\dfrac{d^2y}{dx^2}}{\left[1+\left(\dfrac{dy}{dx}\right)^2\right]^{3/2}} = \frac{\dfrac{d^2y}{dx^2}}{\left(1+\dfrac{v^2}{u^2}\right)^{3/2}} = \frac{\dfrac{d^2y}{dx^2}}{\dfrac{V^3}{u^3}} = g\frac{u}{V^3}$$

(This shows that the equation $\frac{d^2y}{dx^2}=\frac{g}{u^2}$ holds for *any* law of resistance.) Hence the second derivitive of y by x increases inversely as the square of the horizontal velocity or increases exponentially with the arc of the trajectory. For the parabola followed by the bomb in vacuo $U=\infty$ and

$$\frac{d^2y}{dx^2}=\frac{g}{u_0^2} \tag{4'}$$

Inasmuch as

$$\frac{dy}{dx}=\int^x \frac{d^2y}{dx^2}\,dx, \quad y=\int^x\left[\int^x \frac{d^2y}{dx^2}dx\right]dx$$

and since $e^{2gs/U^2}>1$, it follows at once from (4) and (4') that, for a given horizontal travel x, a bomb will fall farther in the air than in vacuo—or, for a given drop h, a bomb will fall short in the air as compared with its position in vacuo. (This would seem to be self-evident, but Hemkel, as translated by Gayhart in "Aviation," cit. sup., states that "the paradox may arise that because of resistance the bomb will travel farther in the air than if in a vacuum"—a remark that I do not understand.)

IV. THE PARABOLA.

If axes be taken at the starting point, the trajectory in vacuo is the parabola

$$y=gx^2/2u_0^2=1/2\ mx^2 \text{ if } m=g/u_0^2.$$

This is the first approximation for the trajectory.

The arc of the parabola $y=1/2\ mx^2$ may be obtained as a series, namely,

$$s=\int^x \sqrt{1+m^2x^2}dx=\int\ (1+1/2\ m^2x^2+\ldots)\ dx=x+1/6\ m^2x^3+\ldots.$$

The approximation is good as long as mx is small relative to 1; it becomes bad as mx nears 1, and for $mx>1$ the series diverges. Now $m=g/u_0^2$. If u_0 is as high as 180 ft./sec., m is as small as 1/1000, and the horizontal travel may be several hundred feet before s differs much from x. If, however, the airplane be moving at only 115 ft./sec., $u_0^2=13{,}200$, $m=g/u_0^2=1/400$, and the horizontal travel can hardly exceed 300 feet before s becomes considerably different from x. As mx is the quantity determining the degree of approximation, the equation $y=1/2\ mx^2$ may best be written as $y=(mx)x/2$, from which it is seen that the drop in vacuo can only be a few hundred feet at best if mx is to remain small. For these small drops the trajectory in air does not depart appreciably from that in vacuo.

V. THE SECOND APPROXIMATION.

The departure from the parabola for moderate drops may be calculated by integrating (4) with $s=x$.

$$\frac{d^2y}{dx^2}=\frac{g}{u_0^2}e^{2gx/U^2}=\frac{g}{u_0^2}\left(1+\frac{2gx}{U^2}\right),\ y=\frac{gx^2}{2u_0^2}\left(1+\frac{2gx}{3U^2}\right),\ \text{approx.} \tag{5}$$

The expansion may be reverted so that x appears as a series in y 1/2.

$$x=u_0\sqrt{\frac{2y}{g}}\left(1+\frac{2gx}{3U^2}\right)^{-1/2}=u_0\sqrt{\frac{2y}{g}}\left(1-\frac{gx}{3U^2}\right),\ x=u_0\sqrt{\frac{2y}{g}}\left(1-\frac{gu_0}{3U^2}\sqrt{\frac{2y}{g}}\right)=u_0\sqrt{\frac{2y}{g}}-\frac{2u_0^2y}{3U^2}. \tag{6}$$

If $u_0/U=1/4$, as might be the case for a high-speed machine and a bomb of low terminal velocity, the correction shows that the bomb in air will fall short of the parabolic position by $-\Delta x=y/24$. As the approximation is only good for values of y running to a few hundred feet, the error in using the parabola is only some 20 feet at most. In case of a slow machine ($u_0=100$) and a high terminal velocity ($U=1{,}500$) the correction would be under 2 feet.

VI. A THIRD APPROXIMATION.

The formula (6) for the horizontal carry is not surely valid for values of y as large as 1,000 feet. It becomes necessary to seek a better integral of (4). The most direct method would

be to expand y into a Maclaurin's series by repeated differentiation of (4). The initial conditions are

$$x=0,\ y=0,\ dy/dx=0,\ s=0 \text{ and } d^2y/dx^2=g/u_0^2,$$

$$\frac{d^3y}{dx^3}=\frac{g}{u_0^2}\cdot\frac{2g}{U^2}e^{2gs/U^2}\sqrt{1+\left(\frac{dy}{dx}\right)^2},\quad \left(\frac{d^3g}{dx^3}\right)_0=\frac{g}{u_0^2}\cdot\frac{2g}{U^2}.$$

From this point on the differentiations become involved. Every time the exponential is differentiated the very small factor $2g/U^2$ is introduced, but with the differentiation of the radical the factor g/u_0^2, which is not so small, is had. The results are

$$\left(\frac{d^4y}{dx^4}\right)_0=\frac{g}{u_0^2}\left(\frac{2g}{U^2}\right)^2,\quad \left(\frac{d^5y}{dx^5}\right)_0=\frac{g}{u_0^2}\cdot\frac{2g}{U^2}\left[\left(\frac{2g}{U^2}\right)^2+\left(\frac{g}{u_0^2}\right)^2\right]$$

The second term in the fifth derivative is large compared with the first if u_0^4/U^4 is a small number—and it is almost always very small. The series for y then becomes

$$y=\frac{gx^2}{2u_0^2}\left(1+\frac{2gx}{3U^2}+\frac{g^2x^2}{3U^4}+\frac{gx}{30U^2}\frac{g^2x^2}{u_0^4}+\text{- - -}\right). \tag{7}$$

The occurrence of the term $(gx/u_0^2)^2$, with the repetition of similar terms in higher powers, makes it clear that not gx/U^2 but gx/u_0^2 is the number which must be kept small if the series is to converge rapidly and be valuable. Now, with reference to the parabolic (first) approximation, $gx/u_0^2=2y/x$; and hence it is inferred that the series expansion (7) is not valid except when $2y/x$ is not large, i. e., when y is not more than a few hundred feet. In fact, a comparison shows that the fourth term in (7) is equal to the second term, which is identical with the correction in (5), when $gx/u_0^2=4.5$. In the case of a machine for which $u_0=100$, $x=1{,}400$. If (7) held good for such large values of x, it would be valid up to drops of some 3,000 feet. This would be very satisfactory, but there is no assurance that the subsequent terms in (7) will be small relative to those already obtained when gx/u_0^2 is as great as 4.5.

However, if the third term of (7) be discarded as small relative to the second, the approximation is

$$y=\frac{gx^2}{2u_0^2}\left(1+\frac{2gx}{3U^2}+\frac{gx}{30U^2}\frac{g^2x^2}{u_0^4}\right)$$

$$x=u_0\sqrt{\frac{2y}{g}}\left(1-\frac{gx}{3U^2}-\frac{gx}{60U^2}\frac{g^2x^2}{u_0^4}\right) \tag{8}$$

$$x=u_0\sqrt{\frac{2y}{g}}-\frac{2u_0^2y}{3U^2}-\frac{gy^2}{15U^2}$$

The correction for the carry x relative to the parabolic path is

$$-\Delta x=\frac{u_0^2y}{3U^2}+\frac{gy^2}{30U^2}=\frac{2u_0^2y}{3U^2}\left(1+\frac{gy}{10u_0^2}\right) \tag{9}$$

and this is probably good up to values of y considerably larger than those for which (6) was proved to hold. For instance, if $u_o=200$, $U=800$, $y=2{,}000$, then $-\Delta x=96$ feet, as figured from (9), is likely to be a fair correction; but if $u_o=100$ it is doubtful whether (9) would be good up to values of y as great as 2,000.

VII. A FOURTH APPROXIMATION.

One way in which to get an estimate of the true trajectory is to shut it in between two curves, one above, the other below it. Clearly $x<s<x+y$. When x is small the relative approach of s to x is close; when s is larger the relative approach to $x+y$ is fairly good. Moreover, $y<s$.

The following three differential equations are therefore suggestive as throwing light on the trajectory

$$\frac{d^2y}{dx^2}=\frac{g}{u_o^2}\,e^{2gx/U^2}, \text{ lying too high,} \tag{10}$$

$$\frac{d^2y}{dx^2}=\frac{g}{u_o^2}\,e^{2gy/U^2}, \text{ lying too high,} \tag{11}$$

$$\frac{d^2y}{dx^2}=\frac{g}{u_o^2}\,e^{2g(x+y)/U^2}, \text{ lying too low,} \tag{12}$$

This first is immediately integrable to give

$$y=\frac{U^4}{4gu_o^2}\left(e^{2gx/U^2}-1\right)-\frac{U^2x}{2u_o^2} \tag{13}$$

This curve leads to the approximation (5) as a special case. It has, however, but small relation to the general features of a long trajectory. The broad fundamental feature of a long trajectory is that the projectile drops vertically at the end, i. e., the trajectory has an asymptote. Obviously, (13) shows no asymptote; every value of x yields a finite value of y.

VIII. A FIFTH APPROXIMATION.

The second equation may be integrated by the usual device of introducing the variable $p=dy/dx$, $d^2y/dx^2=pdp/dy$.
The result is

$$\cos^{-1}e^{-gy/U^2}=\frac{gx}{u_oU} \text{ or } y=\frac{U^2}{g}\log\sec\frac{gx}{u_oU}. \tag{14}$$

This curve, which, like (13), lies above the true trajectory, is a far better approximation when y is large and the curve is nearly vertical. The curve shows an asymptote at $x=\pi u_oU/2g$. The true trajectory can not have an asymptote any farther from the origin. If $u_o=100$ and $U=800$, the total limiting forward travel of the bomb can not therefore be more than 4,000 feet. The asymptotic distance varies directly with both u_o and U. It is in the case of a light object, such as a tennis ball, that the existence of the asymptote is most easily observed.

The correction for forward carry from the parabola to (14) is an underestimate because the true trajectory lies below (14) and consequently nearer the y axis. This correction is

$$-\Delta x=u_o\sqrt{\frac{2y}{g}}-\frac{u_oU}{g}\cos^{-1}e^{-gy/U^2} \tag{15}$$

If $u_o=200$, $U=800$, $y=2{,}000$, as in the previous illustrative case, the correction (an underestimate) is 38 feet as compared with 96, the accuracy of which is unknown. The very different forms of (9) and (15) as functions of u_o are noteworthy.

If $y=2{,}000$, the value of x from (14) is 2,199. For this value of x the value of y in (13), which also undercorrects the parabola, is easiest found from the series

$$y=\frac{U^4}{8gu_o^2}\left[\left(\frac{2gx}{U^2}\right)^2+1/3\left(\frac{2gx}{U^2}\right)^3+1/12\left(\frac{2gx}{U^2}\right)^4+\text{----}\right],$$

which avoids the subtraction of nearly equal large numbers. The value of y is 2,082; hence (13), which lies too high, lies lower than (14) by 82 feet in this case and gives a better trajectory. This might have been expected from the fact that when y is not too large relative to x, s is much nearer to x than to y and (10) must lie nearer the true trajectory than (11).

Now the correction for carry may be found for (13) in this manner. This curve lies 82 feet lower than (14) when $x=2{,}199$ and its slope is nearly 2. The correction from (14) to (13) is therefore 41 feet, which, added to 38, gives 79 as the correction from the parabola as compared with 96 from (9).

IX. A SIXTH APPROXIMATION.

Finally the equation of the curve (12), which is an overestimation, may be integrated. Let

$$z=x+y\frac{dz}{dx}=\frac{dy}{dx}+1,\quad \frac{d^2z}{dx^2}=\frac{d^2y}{dx^2},$$

$$\frac{d^2z}{dx^2}=\frac{g}{{u_o}^2}e^{2gz/U^2},\quad \left(\frac{dz}{dx}\right)^2=\frac{U^2}{{u_o}^2}e^{2gz/U^2}+C.$$

When $x=0$, $y=0$, $z=0$, $dy/dx=0$, then $dz/dx=1$ and $C=1-U^2/{u_o}^2$.

$$\frac{dz}{x}=\sqrt{\frac{U^2}{{u_o}^2}e^{2gz/U^2}-\frac{U^2}{{u_o}^2}+1},$$

$$\cos^{-1}\left(e^{-gz/U^2}\sqrt{1-\frac{{u_o}^2}{U^2}}\right)-\cos^{-1}\sqrt{1-\frac{{u_o}^2}{U^2}}=\frac{gx}{u_oU}\sqrt{1-\frac{{u_o}^2}{U^2}}, \tag{15}$$

$$y+x=\frac{U^2}{g}\left[\log\sec\left(\frac{gx}{u_oU}\sqrt{1-\frac{{u_o}^2}{U^2}}+\sin^{-1}\frac{u_o}{U}\right)+\log\sqrt{1-\frac{{u_o}^2}{U^2}}\right]. \tag{16}$$

This curve, too, shows an asymptote which, when u_o/U is small enough so that its square may be neglected, is in the position

$$x=\frac{u_oU}{g}\left[\frac{\pi}{2}-\frac{u_o}{U}\right]$$

and thus lies nearer the y axis by the absolute amount ${u_o}^2/g$. If $u_o=100$ and $U=800$, as before, the new position of the asymptote falls 310 feet short of the old position. Hence a bomb of terminal velocity 800 ft./sec. launched horizontally from an indefinite height (in an atmosphere of constant density) would have a forward travel approaching some limit between 3,700 and 4,000 feet, approximately.

To return to the case of $u_o=200$, $U=800$, $y=2{,}000$, the best value thus far obtained for x is 2,158 on (13)—an overestimate of x as compared with the true trajectory. Substitute this value in (16). Then $y=2{,}058$ and exceeds 2,000 by 58 feet. As the slope is about 2, this means an additional correction of about 30 feet to $x=2{,}128$. The result is that x lies between 2,128 and 2,158 feet under these conditions. The approximation (9) gave the value $x=2{,}141$—almost the mean, but this may be accidental.

X. SUMMARY.

It has been shown that when a bomb is launched from an airplane the velocity of 800 ft./sec. will not be attained before the bomb has fallen a distance practically equal to that required for attaining the same velocity in vertical fall from rest. Formulas (6) and (9) have been derived for the forward carry (or its correction related to the parabola) in case the vertical fall is only a few hundred feet, but neither formula can be expected to apply when y is larger than x. Three approximate trajectories (13), (14), (16) have been derived. The true trajectory lies below (13) and (14) and above (16). Curves (14) and (16) resemble the true trajectory in showing a vertical asymptote, but until y considerably exceeds x the non-asymptotic form (13) is a better approximation than (14). For an initial velocity as high as 200 ft./sec. and a terminal velocity as low as 800 ft./sec. the correction from the parabola is not great (about 100 ft.) in a drop of 2,000 feet, and the correction is known to within about 15 feet.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
CAMBRIDGE, MASS., *September 22, 1919.*

REPORT No. 80

STABILITY OF THE PARACHUTE AND HELICOPTER

By H. BATEMAN

California Institute of Technology, Pasadena, Calif.

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REPORT No. 80.

STABILITY OF THE PARACHUTE AND HELICOPTER.

By H. BATEMAN.

INTRODUCTION.

This paper was submitted to the National Advisory Committee for Aeronautics by Professor H. Bateman, of the California Institute of Technology, and its publication duly authorized by the committee as Technical Report No. 80.

The mathematical theory of the stability of a parachute which is symmetrical with respect to a plane is very similar to the well-known theory of the stability of an airplane, but the values of the resistance coefficients are naturally different. When the parachute does not rotate, it may be compared with an airplane in a straight dive. There are oscillations corresponding to the longitudinal and lateral oscillations, and these are practically independent of one another. Thus, when the parachute swings like a pendulum as it descends, we have an oscillation corresponding to the pitching of an airplane, while there is another type of oscillation which corresponds to the Dutch roll.

When the parachute is symmetrical about an axis, so that it has the form of a solid of revolution, there may be no banking in the oscillation corresponding to the Dutch roll, and the oscillation then becomes a simple swing like the one which corresponds to the pitching of an airplane. In this case a combination of two simple swings in perpendicular planes may give rise to a compound oscillation, which may be likened to the motion of a conical pendulum falling under gravity. In the general case the combination of the simple swing and Dutch roll gives rise to a compound motion of a complicated character.

ANALYTICAL DISCUSSION.

To discuss the matter analytically we shall write down the equations of motion in the notation used by G. H. Bryan [1] and S. Brodetsky.[2] We shall take the axis of y as axis of symmetry and assume that in the steady state the parachute is falling with velocity V in a vertical direction, which coincides with the axis of y, and is rotating with angular velocity Q around the axis of y. This last assumption is made for the sake of generality, so as to cover the case of a rotating solid of revolution and to obtain a condition corresponding to some extent with the case of the helicopter where the longitudinal and lateral oscillations are not independent. The equations of motion may be written in the form

$$\frac{W}{g}\left[\frac{du}{dt}+(Q+q)w-r(V+v)\right]=W\sin\theta-X,$$

$$\frac{W}{g}\left[\frac{dw}{dt}+p(V+v)-u(Q+q)\right]=-W\cos\theta\sin\phi-Z,$$

$$\frac{A}{g}\frac{dp}{dt}+\frac{A-B}{g}r\,(Q+q)=-L,$$

$$\frac{A}{g}\frac{dr}{dt}+\frac{B-A}{g}p\,(Q+q)=-N,$$

$$\frac{W}{g}\left[\frac{dv}{dt}+ru-pw\right]=W\cos\theta\cos\phi-Y,$$

$$\frac{B}{g}\frac{dq}{dt}=-M.$$

[1] Stability in Aviation.

[2] The Tôhoku Mathematical Journal, vol. 14, August, 1918, p. 116.

Here W is the weight of the parachute and passenger, X, Y, Z, L, M, N the component air forces and couples referred to axes fixed in the parachute, B is the moment of inertia about the axis of symmetry, A the moment of inertia about a perpendicular axis through the center of gravity, both measured in gravitational units, $U+u$, v, w, p, $Q+q$, r are component velocities and spins in the disturbed motion. To obtain the directions of the axes in space in a disturbed position of the parachute we suppose the parachute rotated first about the axis of y (from z to x) through an angle ψ, then about the axis of z (from x to y) through an angle θ, and finally about the axis of x (from y to z) through an angle ϕ.

Let us write $u+iw=a$, $p+ir=b$, $\phi+i\theta=\chi$ where i denotes $\sqrt{-1}$, then since u, w, p, r, θ, and ϕ are small in a small oscillation and the parachute is symmetrical about the axis of y, we may write to a first approximation

$$p=\frac{d\phi}{dt}, r=\frac{d\theta}{dt}, b=\frac{d\chi}{dt}$$

$$X+iZ=aE+bF$$
$$L+iN=aJ+bK$$

where the generalized resistance coefficients E, F, J, K are complex quantities.

The above equations imply that if $E=E_1+iE_2$, etc.,

$$\begin{aligned} &X_u=Z_w=E_1, && Z_u=-X_w=E_2,\\ &X_p=Z_r=F_1, && Z_p=-X_r=F_2,\\ &L_u=N_w=J_1, && N_u=-L_w=J_2,\\ &L_p=N_r=K_1, && N_p=-L_r=K_2,\\ &X_v=O,\ X_q=O, && Z_v=O,\ Z_q=O,\\ &L_v=O,\ L_q=O, && N_v=O,\ N_q=O. \end{aligned}$$

It is on account of these relations that the analysis for the symmetrical parachute is simpler than that for an airplane in a straight drive. If, in fact, we neglect squares of small quantities and use D to denote the operatore $\frac{d}{dt}$ the first four equations may be written in the form

$$\left[\frac{W}{g}(D-iQ)+E\right]a+\left[\left(\frac{WV}{g}-iF\right)D+W\right]i\chi=o,$$

$$Ja+\left[\frac{A}{g}D^2+\left(K+iQ\frac{B-A}{g}\right)D\right]\chi=o.$$

Seeking a solution of the form $a=a_0e^{\lambda t}$, $\chi=\chi_0e^{\lambda t}$ we obtain the period equation $\left[\frac{W}{g}(\lambda-iQ)+E\right]\left[\frac{A}{g}\lambda^2+\left(K+iQ\frac{B-A}{g}\right)\lambda\right]-iJ\left[\left(\frac{WV}{g}-iF\right)\lambda+W\right]=o$. This is a cubic equation with complex coefficients for the determination of λ. When $Q=o$ it reduces to a cubic equation with real coefficients for we have the relations $E_2=o$, $F_1=o$, $J_1=o$, $K_2=o$.

Remembering that in the general case of a rigid airplane the oscillations about a state of steady motion are determined by an algebraic equation of the eighth degree, we infer that in the present degenerate case our real cubic is a double factor of the octic and the periods and decrements are the same for simple swings in two perpendicular planes through the axis of symmetry of the parachute.

When $Q=o$ a root $\lambda=\alpha+i\beta$ for which α is negative and β positive implies the existence of a damped oscillation in which the center of gravity of the parachute describes a curve on a vertical cylinder in such a way that it moves in a counterclockwise direction when the axes are left handed. To see this we notice that $u+iw$ is of the form

$$Re^{\alpha(t-t_0)}\left[\cos\beta(t-t_0)+i\sin\beta(t-t_0)\right]$$

where R and t_0 are real quantities. This equation indicates that $\frac{w}{u}$ increases with t and since

the axis of z is to the left of the axis of x, the axis of y being downwards, this means that the center of gravity moves on the cylinder in the counterclockwise direction.

The equation $\phi + i\theta = X_0 e^{(\alpha+i\beta)t}$ implies that at the same time the axis of symmetry precesses around the vertical in the counterclockwise direction. If we disregard the vertical motion the character of the oscillation may be pictured by imagining a cone representing the parachute to partly roll and partly slide on the outside of another cone whose axis is vertical.

Let us call this a *positive oscillation* and use the term *negative* oscillation to denote one in which β is negative and the two motions take place in the clockwise direction.

Either a positive or negative oscillation can be regarded as built up from two simple swings in perpendicular planes, the two swings having the same period and damping time, but differing in phase by a quarter period. By combining two such swings with an arbitrary difference in phase a type of elliptic oscillation is obtained.

It should be noticed than an *undamped* positive oscillation may correspond to a new type of steady motion of the parachute. If such a motion exist it is characterized by $v=o$, $q=o$ and the fact that the cubic equation has two purely imaginary roots.

Thus cubic equation may be written in the form

$$\lambda^3 + y\lambda^2 + xw\lambda + x = o$$

where

$$x = \frac{g^2 N_u}{A},\ y = g\left(\frac{N_r}{A} + \frac{X_u}{W}\right),\ w = \frac{V}{g} - \frac{1}{W}\left(X_r - \frac{X_u N_r}{N_u}\right).$$

Let $\lambda^2 - 2\alpha\lambda + \theta$ be a factor of the cubic, then α and θ are determined by the equations

$$4\alpha^2 - \theta + 2\alpha y + xw = o$$

$$-2\alpha\theta - y\theta + x = o.$$

With the aid of these equations we can plot the curves $t=$constant in the (x, y) plane. Since

$$(4\alpha^2 + 2\alpha y + xw)\ (y + 2\alpha) = x$$

a curve $t=$constant ($\alpha=$constant) is a hyperbola. When $\alpha = o$ it reduces to $x=o$, $y=\frac{1}{w}$ and this is a boundary of the region of stability in the (x,y) plane. The condition for undamped oscillations is, moreover, either $x=o$ or $y=\frac{1}{w}$.

The asymptotes of the hyperbola $t=$constant are

$$y + 2\alpha = \frac{1}{w} \text{ and } 2\alpha y + xw + 4\alpha^2 + \frac{2\alpha}{w} = o$$

hence when $\theta = -\frac{2\alpha}{w}$ we must have $x=\infty\ y=\infty$. This means that we can not have a value of θ which is smaller than $-\frac{2\alpha}{w}$, consequently when the time of damping is given the period p can not be greater than a certain limiting value P.

If α be given it is clear that P increases with w and so it is desirable that w should be made as large as possible. This can be done either by making V large or by making $X_r - \frac{X_u N_r}{N_u}$ negative and fairly large.

Now V is generally less than $\frac{1}{2}g$ and ought not to be increased beyond this value, consequently the most hopeful method of improving the stability of the parachute is to make $X_r - \frac{X_u N_r}{N_u}$ negative. It is probable that in the Calthrop parachute this condition has been secured.

In Figure I the curves $t=$constant have been drawn for two different values of w. It will be seen that when $w=.25$ the time of damping t is generally greater than the period. This is sometimes the case even when $w=.5$, but by choosing x and y in a suitable manner it is possible to make p greater than t. The importance of a fairly large value of w is thus manifest.

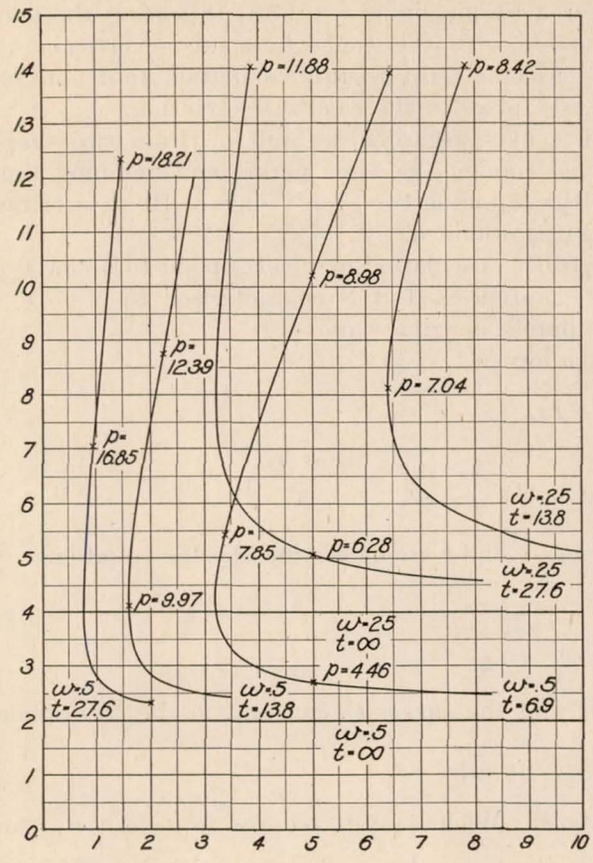


FIG. I.

In his study of the stability of the parachute, Brodetsky treats the parachute as a circular disk attached to a weighted stick and finds from a condition equivalent to $y>\frac{1}{w}$ that the center of gravity must lie between certain limits. The center of gravity must naturally be fairly low, and there seems no way of avoiding this except perhaps by attaching a ring-shaped balloon to the rim of the disk. The upward thrust on the balloon and the downward force through the center of gravity would then have as their resultant a force acting through a point lower than the center of gravity, and this point would act as the center of gravity of the parachute in the usual theory. Unless it could be combined with a helicopter in some way, the combination of a parachute and toroidal balloon would be of theoretical interest only.

Turning now to the case in which $Q\pm O$, we write

$$E=E_0+Q\ (e_1+ie_2) \qquad F=iF_0+Q\ (f_1+if_2)$$
$$J=iJ_0+Q\ (j_1+ij_2) \qquad K=K_0+Q\ (k_1+ik_2)$$

The additional terms involving Q give the forces and couples arising from the Magnus effect or its inverse [1] and from related phenomena.[2] The cubic equation may now be written in the form

$$\Psi(\lambda)\equiv\Phi(\lambda)+Q[(G+iH)\lambda^2+(I+iR)\lambda-iW(j_1+ij_2)]+Q^2[\ \ ]=o,$$

where

$$\Phi(\lambda)=\frac{WA}{g^2}\lambda^3+\frac{E_0A+WK_0}{g}\lambda^2+\left(E_0K_0+J_0F_0+J_0\frac{WV}{g}\right)\lambda+J_0W.$$

$$G=\frac{Ae_1+Wk_1}{g}$$

$$H=\frac{W}{g^2}(B-2A)+\frac{1}{g}(Ae_2+Wk_2),$$

$$I=E_0k_1+K_0e_1+J_0f_2+F_0j_2+\frac{WV}{g}j_2,$$

$$R=E_0k_2+K_0e_2-J_0f_1-F_0j_1-\frac{W}{g}K_0-\frac{WV}{g}j_1+E_0\frac{B-A}{g}.$$

To study the effect of rotation upon the oscillations let λ_0, $\alpha_1+i\beta_1$, $\alpha_1-i\beta_1$ be the roots of the equation $\Phi(\lambda)=o$, λ_0 and α_1 being supposed negative and let $\sigma_0+i\tau_0$, $\sigma_1+i\tau_1$, $\sigma_2+i\tau_2$, be the quantities which must be added to λ_0, $\alpha_1+i\beta_1$, $\alpha_1-i\beta_1$, respectively, to give the corresponding roots of the equation $\Psi(\lambda)=o$. If σ and τ are both positive it means that the effect of rotation is to diminish the period of a positive oscillation and to increase the time of damping t.

[1] For this effect see A. Lafay. Comptes Rendus. Paris. Vol. 151 (1910), p. 867; vol. 153 (1911), p. 1472.

[2] For the effect of sideslip on a propeller see the Technical Reports of the British Advisory Committee for Aeronautics 1912–13, 1913–14, and 1918.

The effect on a negative oscillation is to increase both the period and the time of damping. The effect on a simple subsidence is to make it periodic and increase the time of damping. The effect of rotation when σ and τ are not both positive is easily inferred.

In order that σ_0, σ_1, σ_2 may all be negative and the damping times for the three disturbances associated with λ_0, $\alpha_1+i\beta_1$, $\alpha_1-i\beta$, all increased, it is necessary, but not sufficient, that QG, QI, and Qj_2 should all be positive. Now $N_u=J_0+Qj_2$, hence it is necessary in the first place that the effect of the rotation should be to increase N_u. The effect on the period is of some interest because in general the single period and time of damping associated with the two conjugate roots $\alpha_1+i\beta_1$ and $\alpha_1-i\beta_1$, will give rise to two different periods and two different times of damping; also a new positive or negative oscillation with a long period will arise from the simple subsidence associated with the root λ_0. The phenomenon of the division of one period into two is somewhat analogous to that which occurs in the Zeeman effect, especially as we may have a compound oscillation built up from positive and negative circular oscillations of nearly equal period. The curves in Figure II give the horizontal projection of the path of the center of gravity of the parachute or helicopter in two particular cases of compound oscillations of the above type. In the first case the two component circular oscillations are undamped, in the second case they are both damped, the rate of subsidence being the same in each case. A complete discussion of the effect of rotation on stability is out of the question at present owing to our lack of knowledge of the values of the various resistance coefficients, but it may be worth while to ascertain the conditions for stability by finding the conditions that a cubic equation with complex coefficients may have roots whose real parts are all negative.

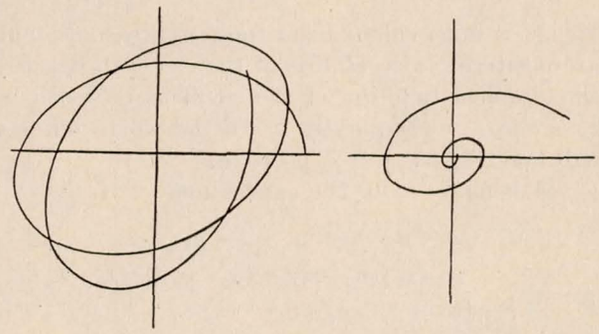


FIG. II.

The conditions that a cubic equation with complex coefficients may have the real parts of all its roots negative.

The method given by E. J. Routh[1] for finding the conditions that an algebraic equation with real coefficients may have the real parts of all its roots negative may be extended to the case of an equation with complex coefficients.

Let us consider the case of the cubic

$$(x+\alpha_1)\ (x+\alpha_2)\ (x+\alpha_3)\equiv x^3+px^2+qx+r\equiv x^3+(p_1+ip_2)x^2+(q_1+iq_2)x+r_1+ir_2$$

Let $\alpha_1=x_1+iy_1$, $\alpha_2=x_2+iy_2$, $\alpha_3=x_3+iy_3$, and let the equation whose roots are $-x_1+iy_1$, $-x_2+iy_2$, $-x_3+iy_3$, be

$$(x+\beta_1)\ (x+\beta_2)\ (x+\beta_3)\equiv x^3+Px^2+Qx+R.$$

In Routh's method the first step is to write iy for x and to separate the real and imaginary parts of the cubic, thus obtaining two expressions

$$y^3+p_2y^2-q_1y-r_2=f_1(y)$$
$$p_1y^2+q_2y-r_1=f_2(y)$$

The process of finding the greatest common measure of $f_1(y)$ and $f_2(y)$ must now be carried out, the sign of the remainder being changed at each step just as in Sturm's theorem. In this way we obtain a series of polynomials whose first coefficients are

$$1,\ p_1,\ \frac{H}{p_1^2},\ \text{and}$$
$$K\equiv\frac{1}{H^2}\{q_2HI-p_1I^2+r_1H^2\}$$

[1] Loc. cit.

respectively, where

$$H = p_1p_2q_2 - q_2^2 - p_1r_1 + p_1^2q_1,$$
$$I = p_1^2r_2 + r_1q_2 - r_1p_1p_2.$$

In order that x_1, x_2, and x_3 may all be positive it is necessary and sufficient that p_1, H, and K should all be positive. The quantity K becomes zero when any one of the quantities x_1, x_2, x_3 becomes zero, it corresponds, therefore, to Routh's discriminant in the case of the real quartic. In terms of x_1, x_2, x_3, y_1, y_2, y_3, the expressions for H and K are

$$H = Ax_2x_3 + Bx_3x_1 + Cx_1x_2,$$
$$H^2K = x_1x_2x_3\,[H^2 - (lC - nA)\ (mA - lB) - (mA - lB)\ (nB - mC) - (nB - mC)\ (lC - nA)]$$

where

$$A = (x_2 + x_3)\ (2x_1 + x_2 + x_3) + (y_2 - y_3)^2,$$
$$B = (x_3 + x_1)\ (2x_2 + x_3 + x_1) + (y_3 - y_1)^2,$$
$$C = (x_1 + x_2)\ (2x_3 + x_1 + x_2) + (y_1 - y_2)^2,$$
$$l = x_1(y_2 - y_3),\ m = x_2(y_3 - y_1),\ n = x_3\ (y_1 - y_2).$$

It is not evident from these expressions that x_1, x_2, and x_3 are positive when p_1, H, and K are positive;[1] also H^2K is of the eleventh degree in the quantities x_1, x_2, x_3, y_1, y_2, y_3, and is not the simplest function of the coefficients which becomes zero when one of the quantities x_1, x_2, x_3 is zero; consequently it will be worth while to find an alternative set of conditions which will make x_1, x_2, and x_3 positive.

Let us consider the expressions

$$\begin{aligned}
T &= (\alpha_1+\beta_1)\ (\alpha_1+\beta_2)\ (\alpha_1+\beta_3)\ (\alpha_2+\beta_1)\ (\alpha_2+\beta_2)\ (\alpha_2+\beta_3)\ (\alpha_3+\beta_1)\ (\alpha_3+\beta_2)\ (\alpha_3+\beta_3)\\
&= 8x_1x_2x_3\,[(x_2+x_3)^2+(y_2-y_3)^2]\,[(x_3+x_1)^2+(y_3-y_1)^2]\,[(x_1+x_2)^2+(y_1-y_2)^2],\\
S &= [(\alpha_2+\beta_2)\ (\alpha_3+\beta_3)+(\alpha_3+\beta_3)\ (\alpha_1+\beta_1)+(\alpha_1+\beta_1)\ (\alpha_2+\beta_2)]\times\\
&\quad [(\alpha_2+\beta_3)\ (\alpha_3+\beta_1)+(\alpha_3+\beta_1)\ (\alpha_1+\beta_2)+(\alpha_1+\beta_2)\ (\alpha_2+\beta_3)]\times\\
&\quad [(\alpha_2+\beta_1)\ (\alpha_3+\beta_2)+(\alpha_3+\beta_2)\ (\alpha_1+\beta_3)+(\alpha_1+\beta_3)\ (\alpha_2+\beta_1)]\\
&= 4[x_2x_3+x_3x_1+x_1x_2]\,[\{x_2+x_3+i(y_2-y_3)\}\ \{x_3+x_1+i(y_3-y_1)\}\\
&\quad +\{x_3+x_1+i(y_3-y_1)\}\ \{x_1+x_2+i(y_1-y_2)\}+\{(x_1+x_2)+i(y_1-y_2)\}\ \{x_2+x_3+i(y_2-y_3)\}]\times\\
&\quad [\{(x_1+x_2)-i(y_1-y_2)\}\ \{x_2+x_3-i(y_2-y_3)\}+\{x_2+x_3-i(y_2-y_3)\}\ \{x_3+x_1-i(y_3-y_1)\}+\\
&\quad \{x_3+x_1-i\ (y_3-y_1)\}\ \{x_1+x_2-i(y_1-y_2)\}],\\
S^1 &= [(\alpha_2+\beta_2)\ (\alpha_3+\beta_1)+(\alpha_3+\beta_1)\ (\alpha_1+\beta_3)+(\alpha_1+\beta_3)\ (\alpha_2+\beta_2)]\times\\
&\quad [(\alpha_2+\beta_3)\ (\alpha_3+\beta_2)+(\alpha_3+\beta_2)\ (\alpha_1+\beta_1)+(\alpha_1+\beta_1)\ (\alpha_2+\beta_3)]\times\\
&\quad [(\alpha_2+\beta_1)\ (\alpha_3+\beta_3)+(\alpha_3+\beta_3)\ (\alpha_1+\beta_2)+(\alpha_1+\beta_2)\ (\alpha_2+\beta_1)]\\
&\equiv [4x_2(x_1+x_3)+(x_1+x_3)^2+(y_3-y_1)^2]\,[4x_1(x_2+x_3)+(x_2+x_3)^2+(y_2-y_3)^2]\times\\
&\quad [4x_3(x_1+x_2)+(x_1+x_2)^2+(y_1-y_2)^2],\\
p_1 &= x_1+x_2+x_3.
\end{aligned}$$

It will be noticed that the second and third factors of S are conjugate complex quantities and so their product is a positive quantity. It is clear then that if p_1, S, and T are all positive, the quantities

$$x_1+x_2+x_3,\ \ x_2x_3+x_3x_1+x_1x_2,\ \ x_1x_2x_3$$

are all positive.[2] Now let x_1, x_2, and x_3 be regarded as the distances of a point from the sides of an equilateral triangle. This is legitimate since $x_1+x_2+x_3$ is positive. Keeping this last quantity constant a point can be used to represent any possible set of values of x_1, x_2, and x_3 whose sum has this constant value.

Now when $x_2x_3+x_3x_1+x_1x_2$ is positive the representative point lies within the circumscribing circle of the triangle and when $x_1x_2x_3$ is positive the representative point lies within

[1] In the case of the quadratic $p_1=x_1+x_2$, $H=x_1x_2\ [(x_1+x_2)^2+(y_1-y_2)^2]=p_1p_2q_2-q_2^2+p_1^2q_1$. When p_1 and H are positive it is evident that x_1+x_2 and x_1x_2 are both positive and that consequently x_1 and x_2 are positive.

[2] When these quantities are all positive S^1 is also positive.

one of the four regions bounded by lines making an acute angle with one another. It is clear then that when $x_1+x_2+x_3$, $x_2x_3+x_3x_1+x_1x_2$ and $x_1x_2x_3$ are all positive the representative point must lie within the triangle and x_1, x_2, x_3, be all positive.

To express S and T in terms of the coefficients we notice that if two of the quantities α_1, α_2, α_3 are interchanged, or if two of the quantities β_1, β_2, β_3 are interchanged, S is transformed into S^1. Hence we are justified in assuming that there is an identity of type

$$S-S^1=k\triangle$$

where

$$\triangle=(\alpha_2-\alpha_3)\ (\alpha_3-\alpha_1)\ \alpha_1-\alpha_2)\ (\beta_2-\beta_3)\ (\beta_3-\beta_1)\ (\beta_1-\beta_2)$$

Comparing coefficients we find that $k=-1$.

Writing S in the form

$$\begin{aligned}S&=(q+Q+pP-\alpha_1\beta_1-\alpha_2\beta_2-\alpha_3\beta_3)(q+Q+pP-\alpha_3\beta_1-\alpha_1\beta_2-\alpha_2\beta_3)(q+Q+pP-\alpha_2\beta_1-\alpha_3\beta_2-\alpha_1\beta_3)\\&=(q+Q+pP)^2(q+Q)+(q+Q+pP)(p^2Q+P^2q-3qQ)-U\end{aligned}$$

where

$$U=(\alpha_1\beta_1+\alpha_2\beta_2+\alpha_3\beta_3)\ (\alpha_3\beta_1+\alpha_1\beta_2+\alpha_2\beta_3)\ (\alpha_2\beta_1+\alpha_3\beta_2+\alpha_1\beta_3)$$

we assume that

$$-U+\frac{1}{2}\triangle=ArR+B(rPQ+Rpq)+C(rP^3+Rp^3)+DPQpq+Ep^3P^3+F(p^3PQ+P^3pq)$$

Determining the unknown coefficients by putting

(1) $\alpha_1=o,\ \beta_1=o,$

(2) $\beta_2=o,\ \beta_3=o,$

(3) $\alpha_2=\alpha_3,\ \beta_1=o,$

(4) $\beta_1=\beta_2=\beta_3,$

we find that

$$A=-\frac{27}{2},\ B=\frac{9}{2},\ C=-1,\ D=-\frac{1}{2},\ E=o,\ F=o.$$

Hence finally

$$\begin{aligned}S=&(q+Q)(q+Q+pP)^2+(q+Q+pP)(p^2Q+P^2q-3qQ)-\frac{27}{2}rR+\frac{9}{2}(rPQ+Rpq)\\&-rP^3-Rp^3-\frac{1}{2}PQpq-\frac{1}{2}\triangle,\end{aligned}$$

$$\triangle^2=(p^2q^2-4p^3r+18pqr-4q^3-27r^2)\ (P^2Q^2-4P^3R+18PQR-4Q^3-27R^2)$$

Writing T in the form

$$T=(\alpha_1{}^3+P\alpha_1{}^2+Q\alpha_1+R)\ (\alpha_2{}^3+P\alpha_2{}^2+Q\alpha_2+R)\ (\alpha_3{}^3+P\alpha_3{}^2+Q\alpha_3+R)$$

we easily find that

$$\begin{aligned}T=&r^3+R^3+Pr^2q+pR^2Q+Qrq^2+qRQ^2-2Qpr^2-2qPR^2+3Rr^2+3R^2r+Rq^3+rQ^3-3Rpqr-3rPQR\\&+P^2pr^2+p^2PR^2+P^3r^2+p^3R^2+PQpqr+pqPQR+P^2Qqr+p^2qQR+PQ^2pr+pq^2PR+P^2Rq^2\\&+p^2rQ^2-2P^2Rpr-2p^2rPR-3r^2PQ-3R^2pq-QRpr-qrPR-2q^2QR-2Q^2qr.\end{aligned}$$

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COMPARISON OF UNITED STATES AND BRITISH STANDARD PITOT-STATIC TUBES

By A. F. ZAHM AND R. H. SMITH

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By A. F. Zahm and R. H. Smith.

PREFACE.

It has been stated by some experimenters that the standard pitot-static tube used by the United States Navy does not, at all airplane speeds, give the same differential pressure as the British standard pitot-static tube. Since the readings of these two tubes form the basis of comparison of a part of the British and American aerodynamic data, it was deemed advisable to calibrate them with reference to one another at all available wind tunnel speeds. This was accomplished in the 8 by 8 foot tunnel constricted to 4 by 4 feet and giving a fairly uniform air flow at all speeds up to 160 miles an hour. The table and illustrations were prepared by Mr. G. C. Hill.

DESCRIPTION OF TUBES.

Figs. 1, 2, 3, and 4 give the general exterior appearance of these instruments and the structural drawings of their nozzles. In shape both nozzles consist of round coaxial tubes terminating in a hollow conical nose with fine external taper as shown in the figures. The Navy tube has the steeper taper and the greater number of static holes in the external pipe. The holes in both are 0.040 inch in diameter. Both nozzles are attached to stream-line shanks which convey the static and impact pressures, respectively, to the opposite leads of their manometers or pressure gauges. The theory and general structure of such tubes are too well known to require detailed explanation.

MANNER OF TESTING.

During calibration the tubes were placed abreast in the 4 by 4 foot tunnel, equally distant from each other and from the walls, and supported from their shanks which ran vertically upward through the ceiling of the tunnel to liquid alcohol manometers having a 1 to 5 slope. Vibration was prevented by a fine wire attached to the lower ends of the shanks and to the side walls. During the test the British tube was made to read even miles per hour from 20 to 160, by increments of 10, and the corresponding pressure difference for the other tube was observed at the same instant, at the time when both readings were steady. After a complete and careful run, duly checked, the tubes were interchanged in position, and a complete new run was taken with the British tube still made the instrument of reference. The mean of the speed indications of the Navy tube, observed at any one speed in the two positions, was taken as the true reading, or what would be obtained in a uniform and homogeneous current.

By means of a hook gauge, the two manometer tubes were calibrated to 0.001 of an inch of water simultaneously and under the same pressure, allowance being made for the descent of the alcohol in their reservoirs. As seen from Table I and Fig. 5, the two straight glass tubes of the inclined manometer were of uncommonly uniform diameter, except where a weld in each tube was made during construction. Both were of German glass 3/16 of an inch in diameter. The meniscus could be located accurately to 0.01 of an inch along the tube, or 1/500 of an inch in vertical displacement, thus enabling the differential pressure in the nozzles to be read truly to less than 1 per cent at 20 miles per hour and still more accurately at higher speeds.

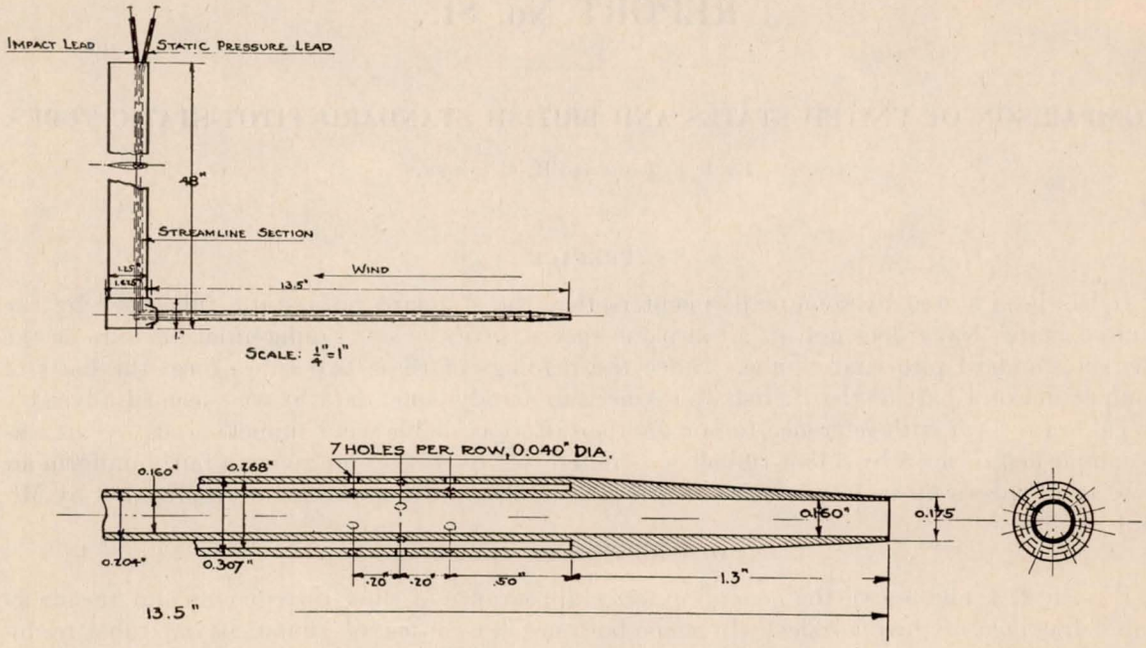


FIG. 3.—British pitot-static tube.

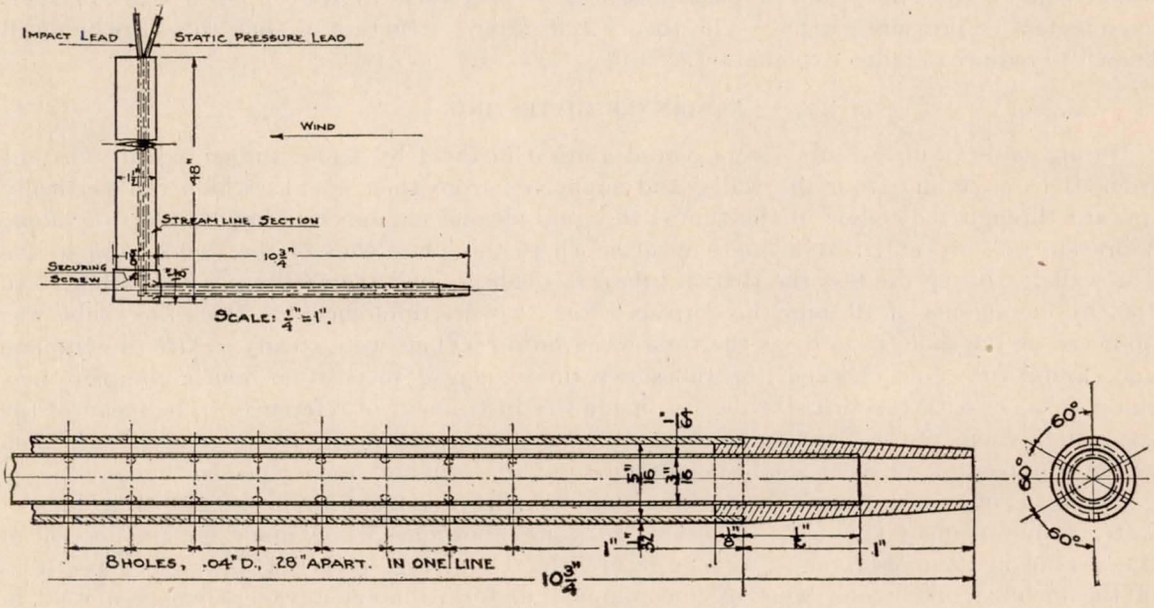


FIG 4.—U. S. Navy pitot-static tube.

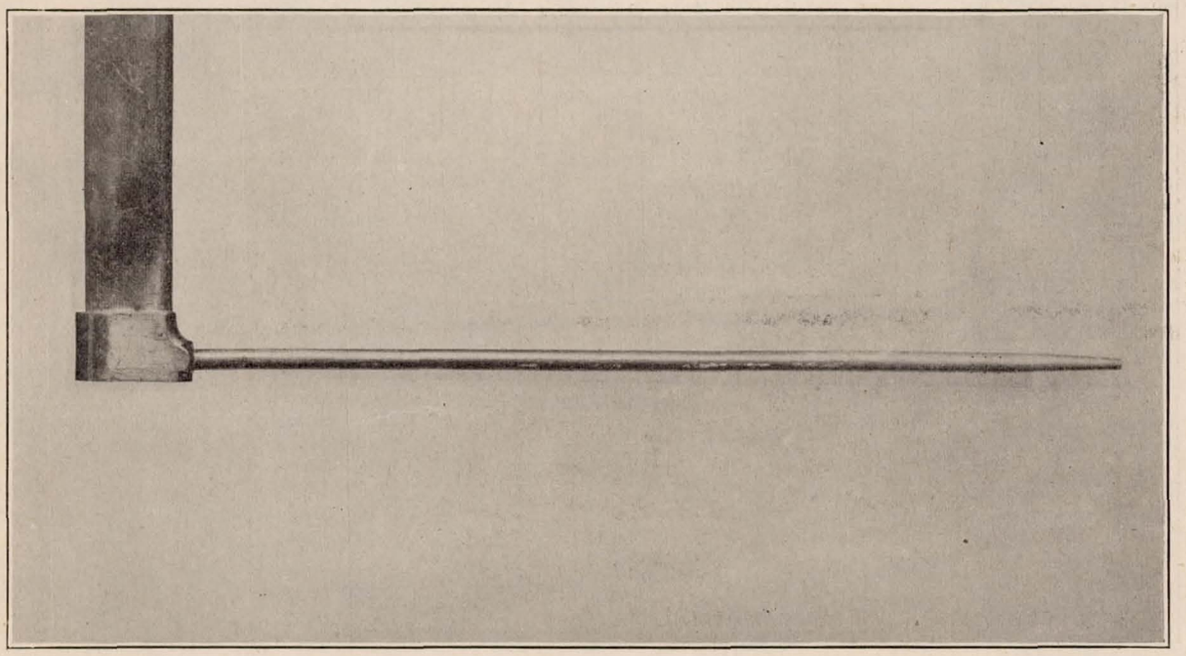


FIG. 1.—STANDARD BRITISH PITOT-STATIC TUBE.

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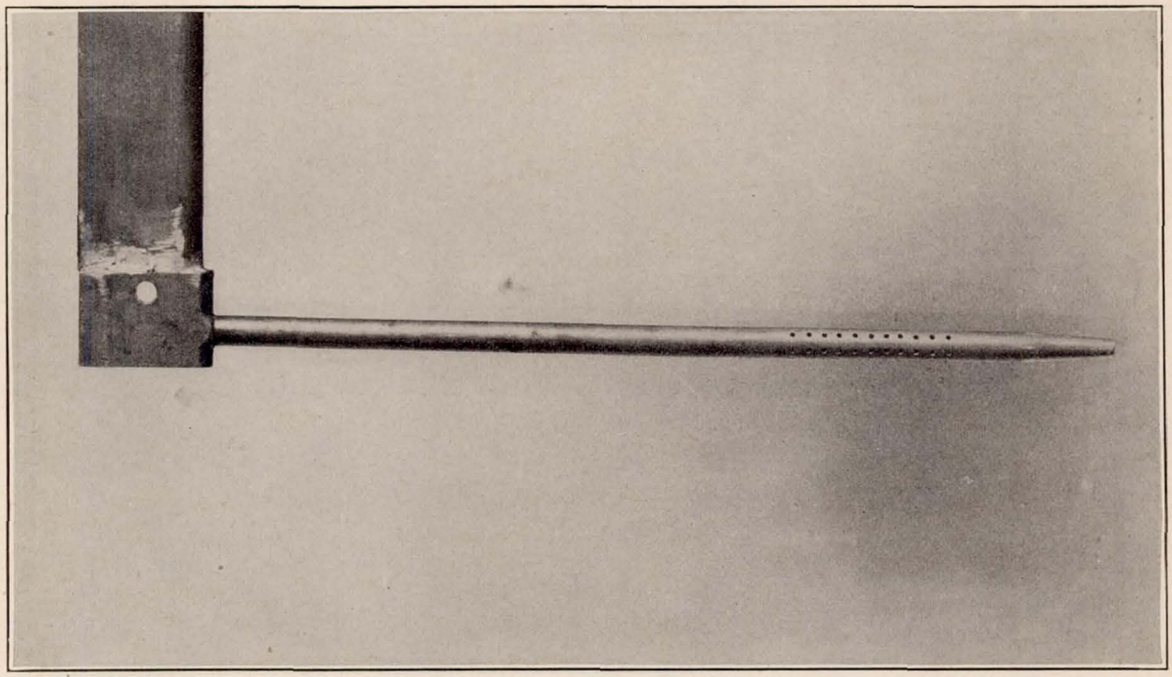


FIG. 2.—U. S. NAVY STANDARD PITOT-STATIC TUBE.

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RESULTS.

Fig. 6 gives the final calibration data for the two tubes. When the corrected air speed indications of the United States Navy tube are plotted to the same linear scale, against those of the British tube, as a basis of reference, the data all lie on a straight line whose slope is unity. It had been alleged that the somewhat steeper cone of the Navy nozzle caused too low pressure in the static holes. From this diagram, however, it appears that the air speed readings of the two instruments are identical to the accuracy of indication of either instrument.

REMARK.

It seems most desirable that a standard pitot-static tube be accurately calibrated at all speeds used in aerodynamic research. The precise calibrations thus far made have stopped far short of the speeds available in modern wind tunnels and aircraft.

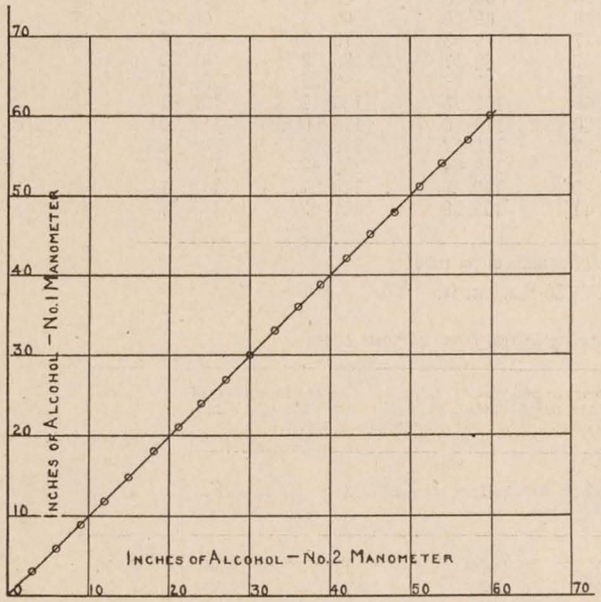


FIG. 5.—Readings of manometers 1 and 2 under same pressure.

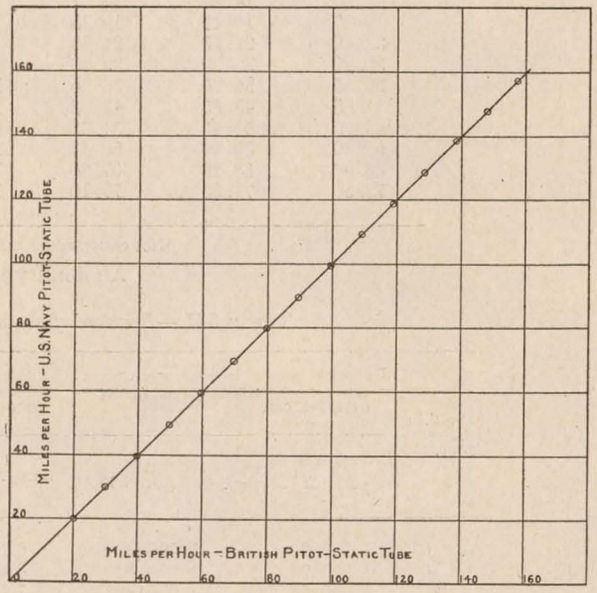


FIG. 6.—Simultaneous air speed indications of two pitot-static tubes.

TABLE I.—*Readings of two manometers under same pressure.*

[Inches of alcohol on 1/5 slope.]

Manometer No. 1.	Manometer No. 2.
3. 00	3. 01
5. 97	5. 98
8. 96	8. 96
11. 93	11. 93
14. 93	14. 94
17. 97	18. 00
20. 98	21. 00
23. 96	23. 99
27 01	27. 02
30. 03	30. 03
33. 03	33. 03
36. 01	36. 00
38. 94	38. 93
42. 06	42. 00
45. 10	45 00
48. 06	47. 90
51. 07	51. 03
54 08	53. 96
57. 10	57. 03
59. 96	59. 99

TABLE II.—*Speed comparison of United States and British pitot-static tubes.*

Observed inches of alcohol on 1/5 slope.			Air speed.			
			$V=\sqrt{\frac{2}{\rho_o}p}$		$V=\left[\left(\frac{2\gamma}{\gamma-1}\frac{p_o}{\rho_o}\left(1-\left(\frac{p}{p_o}\right)^{\frac{\gamma-1}{\gamma}}\right)\right)\right]^{\frac{1}{2}}$	
British tube.	United States tube.		British tube m. p. h.	(Mean) United States tube m. p. h.	British tube m. p. h.	(Mean) United States tub m. p. h.
	(First position).	(Second position).				
1. 21	1. 23	1. 21	19. 95	20. 03	19. 95	20. 03
2. 71	2. 73	2. 71	29. 85	29. 92	29. 85	29. 92
4. 83	4. 85	4. 82	39. 85	39. 85	39. 85	39. 85
7. 55	7. 57	7. 53	49. 83	49. 83	49. 80	49. 80
10. 85	10. 88	10. 85	59. 76	59. 78	59. 71	59. 73
14. 80	14. 84	14. 77	69. 76	69. 76	69. 63	69. 63
19. 35	19. 40	19. 35	79. 77	79. 83	79. 58	79. 64
24. 40	24. 45	24. 33	89. 57	89. 57	89. 32	89. 32
30. 20	30. 30	30. 18	99. 68	99. 73	99. 28	99. 33
36. 55	36. 70	36. 55	109. 65	109. 75	109. 11	109. 21
[1]51. 05	43. 65	43. 52	119. 60	119. 60	118. 90	118. 90
[1]43. 50	51. 40	51. 05	129. 57	129. 57	128. 66	128. 66
59. 20	59. 40	59. 10	139. 56	139. 64	138. 42	138. 50
68. 00	68. 20	67. 80	149. 49	149. 49	148. 07	148. 07
77. 30	77. 35	77. 10	159. 41	159. 38	157. 62	157. 57

[1]Not corrected for weld in glass manometer tube.

Air density ρ_o=.07635 lbs./cu. ft.

TABLE III.—*Pressure of air on coming to rest from various speeds.*

Air speed in miles per hour.	Barometric plus impact pressure in standard atmospheres, i. e., in megadynes/sq. cm.		Impact pressure in pounds per square foot: 1 megadyne/sq. cm.=2,088 lbs. sq./ft.[1]		Impact pressure in inches of water: 1 megadyne/sq. cm.=401.8 in. of water.[1]		Percentage difference.
	Incompressible. $p=1+\frac{\rho_o V^2}{2}$	Adiabatic $p=(1+.000001747\ V^2)^{3.5}$	Incompressible.	Adiabatic.	Incompressible.	Adiabatic.	
0	1. 000000	1. 000000	0. 0000	0. 0000	0. 0000	0. 0000	0. 00
10	1. 000122	1. 000122	0. 2547	0. 2547	0. 0490	0. 0490	0. 00
20	1. 000488	1. 000488	1. 0189	1. 0189	0. 1965	0. 1965	0. 00
30	1. 001099	1. 001099	2. 2947	2. 2947	0. 4416	0. 4416	0. 00
40	1. 001954	1. 001954	4. 0800	4. 0800	0. 7851	0. 7851	0. 00
50	1. 003052	1. 003054	6. 3726	6. 3768	1. 2263	1. 2271	0. 07
60	1. 004396	1. 004400	9. 1788	9. 1872	1. 7662	1. 7683	0. 12
70	1. 005983	1. 005994	12. 4925	12. 5155	2. 4040	2. 4084	0. 18
80	1. 007814	1. 007833	16. 3156	16. 3553	3. 1397	3. 1473	0. 24
90	1. 009890	1. 009921	20. 6503	20. 7150	3. 9738	3. 9863	0. 31
100	1. 012210	1. 012259	25. 4945	25. 5968	4. 9060	4. 9257	0. 40
110	1. 014774	1. 014847	30. 8481	31. 0005	5. 9362	5. 9655	0. 49
120	1. 017582	1. 017687	36. 7112	36. 9305	7. 0645	7. 1066	0. 59
130	1. 020635	1. 020780	43. 0859	43. 3886	8. 2911	8. 3494	0. 70
140	1. 023932	1. 024130	49. 9700	50. 3834	9. 6159	9. 6954	0. 82
150	1. 027472	1. 027733	57. 3615	57. 9065	11. 0383	11. 1443	0. 95
160	1. 031259	1. 031594	65. 2669	65. 9683	12. 9126	13. 0589	1. 06
170	1. 035311	1. 035755	73. 7292	74. 6564	14. 1879	14. 3664	1. 26
180	1. 039587	1. 040147	82. 6585	83. 8269	15. 9062	16. 1311	1. 45
190	1. 044108	1. 044804	92. 0977	93. 5508	17. 7226	18. 0022	1. 58
200	1. 048873	1. 049728	102. 0475	103. 8321	19. 6373	19. 9807	1. 75

[1] See Report No. 20, United States National Advisory Committee for Aeronautics, Third Annual Report, p. 400.

$$p=p_o\left(1+\frac{(\gamma-1)\rho_o V^2}{2\gamma p_o}\right)^{\gamma/\gamma-1}$$
$$=(1+0.000001747\ V^2)^{3.5}$$

p_o=1 megadyne/sq. cm.
ρ_o=0.001223 gm./cu. cm.
γ=1. 40.
V=meters per sec.

NOTE.—Using γ=1.405 would lower values in columns 5 and 7 less than 0.02 per cent for speeds below 200 miles an hour.

REPORT No. 82

AIRPLANE STRESS ANALYSIS

IN FIVE PARTS

By A. F. ZAHM

WITH PROBLEMS AND DIAGRAMS

By L. H. CROOK

Aerodynamical Laboratory, Bureau of Construction and Repair, U. S. Navy

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REPORT NO. 82.

PREFACE.

With each delivery of a new type or size of airplane the manufacturer furnishes (1) the data and (2) the computations by which to judge the performance and safety of the machine.

Under "data" may be classed the geometrical dimensions of the entire craft and its parts; the physical properties of its materials, both raw and as treated for final use, and a description of the method of treatment of these materials; the measured strengths of the whole structure and of its elements; the weight schedule, giving the mass and position of the structural parts and of the carried loads; the aerodynamic properties of the sustaining and control surfaces, the body, the undercarriage, and the craft as a whole; the records of inspection and full-scale test, etc. To this must be added much special information about the engine, the propeller, the navigating instruments, etc.

Under "computations" may be furnished information as to the stresses and performance of (1) the motor; (2) the screw; (3) the craft as a whole.

The present work, intended as a handbook, covers primarily the theory of airplane stress analysis, but ignores, as foreign to its scope, the forces within the engine and propeller. It presents analytical methods and formulas with little if any argument, assuming the reader can supply the proofs or will not require them. All the formulas are illustrated by problems given immediately in the text and solved in Chapter IV.

Acknowledgment is here made to the Journal of the Franklin Institute for a part of the diagrams and subject matter which the writer previously had published in that periodical; to the Curtiss Aeroplane & Motor Corporation for practical data used in the problems; and to Mr. L. H. Crook, Mr. N. C. Luther, and Mr. R. H. Smith for assistance in revising the text and reading the proofs. The aerodynamic data have been taken partly from reports of the bureau of Construction and Repair partly from those of other laboratories. A portion of the wing-stress equations, taken from this work, will appear in the bureau's forthcoming book entitled "Aircraft Design Data."

A. F. ZAHM.

JANUARY, 1918.

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REPORT NO. 82.

PART I.

GENERAL CONSIDERATIONS.

By A. F. Zahm.

INTRODUCTION.

This report was prepared at the Aerodynamical Laboratory, Navy Yard, Washington, D. C., by direction of Rear Admiral D. W. Taylor, Chief Constructor, U. S. Navy, and Member of the National Advisory Committee for Aeronautics, for publication in the committee's Fifth Annual Report.

1. TERMINOLOGY.

The mechanical terms in this text bear the same meaning as in standard works on applied mechanics; the aeronautical terms, where practicable, follow the nomenclature published in 1917 by the United States National Advisory Committee for Aeronautics (Report No. 25). Some words not so published are used of necessity, and when of uncertain meaning are defined upon their first appearance in the text. For example, "air force" for the resultant of air pressure and friction. As an abbreviation for "angle of incidence," the term "incidence" is sometimes used in this text, as is commonly done in aerodynamic works.

2. UNITS AND DIMENSIONS.

For the most part in this text ordinary British units are employed. The unit of mass is sometimes the pound; sometimes the slug, or g pounds, g being the acceleration of gravity.

The standard of air density is taken as 0.07635 pound, or 0.00238 slug, per cubic foot, or that of dry air at 760 m. m. and 15.6° C. Hence the familiar full impulse ρV^2, per unit cross section of a jet, is $0.00238\,V^2$ pound per square foot when V is feet per second, or $0.0051\,V^2$ when V is miles an hour. And the air force on a normal surface of A square feet is $R = 0.00238\ CAV^2$ pounds at V feet per second, C being a dimensionless multiplier, called the "shape coefficient," or "absolute coefficient"—a constant independent of the system of units.[1]

3. NORMAL AND ABNORMAL LOADS.

Structurally an airplane is under normal load in two notable cases: (1) On earth when resting naturally on a level surface; (2) in air when in steady straightaway flight at any incidence.[2] In these cases the external applied forces, whether due to air, earth, or motor, are constant and in algebraic sum equal to the weight of the craft. Some may be positive, others negative.

In all other conditions the loading is abnormal and may be either constant or not; either uniformly increased or not; either positive or negative. For example, an airplane in steady flight around a level circular course bears a constant load determined by the speed and curvature. For this case the actual load in terms of the normal is tabulated in figure 5. For the large path curves there shown the increase of loading is substantially uniform throughout the structure. Again the craft may be diving steeply at steady speed and incidence. Then its loading, both lift and drift, is constant; the first smaller than normal, the second larger. When the machine is standing on earth some of the loads are reversed from their direction in air; when flying inverted all "lift" loads are reversed.

[1] In general, the same formula applies to an inclined flat surface whose face area is A, so long as its incidence and orientation remain constant.

[2] The loading due to the general air stream is illustrated in figs. 1, 2, 3, 4 for a typical monoplane surface.

4. SUDDEN LOADS.

Inconstant abnormal loads may arise from sudden changes of air speed or incidence, as in diving, or riding gusts; from motor jerking; from impact against earth or water, etc.; and their change may be uniform throughout the structure or localized; uniform or irregular in growth and decay. But frequently it suffices to assume that all parts of the structure sustain the same acceleration and hence the same change of load. If this acceleration be j at any part of the airplane, the masses in that part induce stresses j/g times those due to their weight alone, assuming j and g in the same direction.

When practicable in engineering tests, an accelerometer should be carried in the active machine to record the component accelerations in the air and on the earth. To find j throughout the craft, it is well to use several accelerometers distributed throughout the structure.

Sometimes the acceleration is estimated from observed or assumed data. For example, suppose that a craft, regarded as a single rigid mass in pure translation, lands with vertical velocity component v, whose "head" is $h=v^2/2g$, and comes to rest with *uniform* cushioning, of yield d.[1] Then the ratio of its average vertical acceleration to gravity is[2]

$$j/g=1+h/d. \tag{1}$$

It is twice this amount if, as rarely happens, the cushion resistance be directly proportional to the cushion deflection d.

Equation (1) is true not only of the machine as a whole, but of every part of it, however elastic the structure. If the craft approach land in pure translation, h is the same for all elements, but d varies throughout the structure, being least in the chassis parts and greatest in the parts remote from the impact points. A like treatment applies to longitudinal and lateral accelerations.

The assumed maximum acceleration to be provided for in the design of an airplane is usually specified by the purchaser.

Example 1.[3]—If an accelerometer fixed to an airplane records a maximum vertical acceleration of 48 feet per second, what is the ratio of the abnormal to the normal loading?

Example 2.—An airplane in landing has a vertical velocity component of 10 feet per second and a uniform cushion yield of 6 inches. Find the ratio of the abnormal to the normal stresses in the landing gear, assuming the machine to be a rigid structure

5. SIMPLE STRESSES.

The *direct simple stresses* here treated are the common tensile, compressive, and shearing stresses. For each the intensity or unit stress is uniform over the cross section and is given by

$$S=P/A, \tag{2}$$

P being the load sustained by the structural cross section A. For each case the load and stress have the same direction. For torsion in a round shaft the intensity of direct shearing stress at different points of a cross section varies directly with the radius to those points and in the outermost fiber is

$$S=Mc/J \tag{3}$$

where M is the torsional moment, c the distance from the center of gravity to the outermost fiber, J the polar moment of inertia of the section.

6. INDIRECT SIMPLE STRESSES.

Indirect simple stresses perpendicular to the applied loads occur in transverse and in torsional loading. In both cases the longitudinal and the transverse shearing stresses at any point are equal.

---

[1] The cushion force may be partly air lift, partly spring lift. The air lift diminishes slightly with v; the spring lift increases with d, though seldom directly as the deflection, depending on the nature of the cushioning mechanism. In general, the longer the yield, d, the less the shock, or mean vertical acceleration.

[2] To prove (1) equate the work of cushioning to the work of total fall:

$$\text{thus} \quad Mjd=Mg(h+d),$$
$$\text{whence} \quad j/g=1+h/d,$$

in which M is the mass of the machine, j the average cushioning retardation.

[3] The solutions to all the examples cited in the text are given in Part IV.

In transverse loading the tension or compression is greatest in the outermost fibers of the beam and is

$$S = Mc/I, \tag{4}$$

where M is the bending moment, I the moment of inertia of the cross section.

In a beam so loaded the longitudinal shearing stress varies over any cross section, being zero at the remotest fiber and increasing toward the neutral axis of that section. At any reference axis Y in the section, parallel to the neutral axis, the horizontal shear is

$$S = ac\ V/It \tag{5}$$

where a is the sectional area outward from Y, c the distance of the centroid of a from the neutral surface, V the total shear over the entire beam section, and t the thickness of the beam at Y. In most, but not all, practical cases the horizontal shear is a maximum at the neutral surface. Its value there is, for a round beam, 4/3 the mean vertical shear V/A; for a rectangular one 3 $V/2$ A.

Example 3.—Find the longitudinal shearing stress in a 4-inch square beam given the total vertical shear as 1,400 pounds; first with the diagonal vertical, then with it inclined 45°.

7. RESULTANT UNIT STRESS.

When several causes simultaneously produce like stresses at any point in a structure, these may be algebraically added.

(*a*) *Endwise stresses due to simultaneous endwise and transverse loads.*—Several endwise stresses may occur at a point simultaneously. Thus in the lower rear spar of an airplane the lift produces tension, the drag compression; the bending moment produces tension and compression. The algebraic sum of all these is the effective stress. If P be the aggregate endwise stress, the above operation is expressed by the following equation,

$$S = P/A \pm M/Z, \tag{6}$$

in which M is the bending moment due to the running load only, z, the section modulus. The obvious physical meaning of this equation is that the first term represents the unit direct stress, the second term the unit bending stress, which may be taken either as tensile or compressive.

A more accurate formula for the total endwise unit stress here considered is

$$S = P/A + M/Z + k^1Pd/Z, \tag{7}$$

in which d is the deflection due to M only (computed as in figs. 13, 14, 15, 16), and k is a correction factor to be applied to d, because the latter is slightly increased by P.

If in (6) and (7) P/A is a tensile stress, the succeeding terms can be reduced to "equivalent tensile stress" by multiplying them by S_b/S_t, or the ratio of the bending to the tensile strength of the material. This is sometimes done when S_b differs materially from S_t. Similarly, when P/A is a compressive stress. The equation (6) then assumes the form

$$S = S_t + r\,M/Z \tag{8}$$

where S is the equivalent tensile stress and r is the ratio of the tensile to the bending strength of the material. The equivalent compressive stress is similarly found.

Formulas (6), (7), may be used for wing spars and for non-tapering flat struts bearing a considerable side wind pressure. But if the strut be tapering, S can not be found by formula (7) here presented, since d is unknown. However, for normal flying conditions the deflection is ignored, since there is no appreciable side wind against the strut.

Example 4.—Find the resultant unit stress in a 2-inch square simple beam, due to an endwise load of 900 pounds, a maximum bending moment of 1,100 inch-pounds, and a maximum deflection of 0.05 inch at the place of maximum moment.

---

[1] By a well-known approximate formula $k = \sec \frac{l}{2}\sqrt{P/EI}$.

(*b*) *Endwise stresses due to simple endwise loads accompanied by bending.*—For a uniform column or strut bearing an endwise load, but no transverse one, the unit actual stress in the outermost fiber is usually found by Rankine's formula

$$S=[1+a(l/r)^2]P/A, \tag{9}$$

in which P is the actual end load producing stresses lower than the elastic limit, l is the length of the strut, r its least radius of gyration at the center section, and a is a numerical constant depending on the material, strut form, and manner of constraining the ends.[1] Values of a for various materials, forms, and end conditions are given in books on applied mechanics.

If the endwise load is distant p from the column axis the unit stress is

$$S=[1+a(l/r)^2+cp/r^2]\ P/A \tag{10}$$

where c is the distance of the remotest fiber, and r is the radius of gyration.

Example 5.—Find the unit stress in a pin-ended column 1 inch square and 30 inches long under an axial load of 200 pounds; also the unit stress when taking the eccentricity of the load as 2 inches.

(*c*) *Combined shearing and normal stress.*—If at any point of a section, S is the normal unit stress, and S_s the transverse or the equal longitudinal shearing unit stress, then at that point the maximum resultant shearing stress S_p, and maximum normal stress S_n are, respectively

$$S_p=\sqrt{S_s^2+(S/2)^2} \tag{11}$$

$$S_n=S/2\pm S_p \tag{12}$$

Example 6.—A beam is subject to a compressive unit stress of 200 pounds per square inch and at the same time to a longitudinal shearing stress of 250 pounds per square inch. Compute the maximum resultant stresses.

8. REPETITIVE AND EQUIVALENT STRESS.

When a variable load stresses a member frequently through a fraction m of its elastic limit, the *equivalent steady stress* may be taken as

$$S'=S(1+m)^n \tag{13}$$

where S is the allowable constant stress, and n is unity for very numerous stress fluctuations, zero for very few.[2]

Example 7.—If a member whose allowable constant stress is 20,000 is stressed frequently to 15,000 and has an elastic limit of 60,000, what is the equivalent stress?

9. MAXIMUM STEADY LOAD AND STRESS.

For a member subject to uniform simple stress the greatest possible load it will sustain is

$$P=SA \tag{14}$$

S being the strength of the material, and A the sectional area of the member. Examples in airplane construction are: For tension, the stays; for compression, the short struts; for shear, the clevis pins. In all such cases the maximum load and maximum unit stress occur together.

For a structural element not subject to uniform simple stress the greatest possible load may exceed that causing the greatest stress. A long strut, for example, may bear a greater endwise load and sustain less fiber stress before much bending occurs than when bowed excessively.

For a pin-ended wooden strut having a slenderness ratio l/r, above 120, the maximum load is computed by Euler's formula

$$P_{max}=\pi^2 EI/l^2 \tag{15}$$

where l is the length between pins, I the least moment of inertia of the middle section.

For pin-ended struts with a lower slenderness ratio Johnson's formula

$$P_{max}=AC(1-Cl^2/40Ek^2) \tag{16}$$

---

[1] See Rankine's Applied Mechanics, section 328. The use of formula (9) for computing P_{max} is not recommended, formulæ (15), (16) giving better results.

[2] See Upton, Materials of Construction, section 215.

is used, where A is the middle section area, C the crushing strength of the material, k the least radius of gyration of the middle section. If the strut has very securely fixed ends, the above two values of P_{max} may be quadrupled.

The crippling load on any strut or column is sometimes given as a function of the slenderness ratio l/r, in tables or diagrams derived from laboratory tests of full scale test pieces.

Example 8.—Find the maximum load for a pin-ended spruce column of length 60 inches, cross section 3 square inches, and moment of inertia 0.3 inch ^{4}.

10. FACTORS OF SAFETY.

Given the resultant fiber stress intensity, this may be divided into an assumed limiting stress to find the strength-stress ratio, commonly called the "factor of safety." The limiting stress is determined from standard test pieces of the material and of the structural forms in question. For each material and form employed in the industrial arts the assumed limiting stress is commonly fixed by agreement between the constructor and the purchaser. For stays, turnbuckles, fastenings, etc., and sometimes for struts—also for entire truss members, wings, fuselages, etc.—the factor of safety is taken as the ratio of the greatest possible load to the greatest actual load of the member, the former load being found experimentally, the latter either by calculation or by instrumental test under working conditions either real or simulated.

Example 9.—Find the factors of safety in example 6 for a maximum shearing stress of 1,000 pounds per square inch, and a maximum compressive stress of 4,000 pounds per square inch; also the factor of safety in example 8 for an applied load of 250 pounds.

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PART II.

AIRPLANE WING STRESSES.

By A. F. Zahm.

11. SCOPE OF TREATMENT.

The study of wing stresses may cover in succession the fabric, the ribs, the ailerons, the spars as beam members, the lift and drag trussing. From the resultant stresses so found are computed the factors of safety for steady normal flight, taking account of the known strength of the individual members or of their dimensions and materials.

12. WING FABRIC LOADING AND STRESS.

The tensile stress in the fabric at any point of a wing surface may be computed from the given curvature and air-pressure distribution at that point. Typical external pressure distributions on a monoplane surface are shown in figures 1, 2, 3, and 4. The internal pressure is sensibly constant and unknown, but with impervious fabric may be made equal to the external surface pressure at any point by perforating the canvas there.

At any part of the surface, as in figure 6, let p be the resultant point pressure of the air in pounds per square foot, a the distance in inches between ribs, and c the depth in inches of the bulge in the canvas midway between the ribs; then the fabric tension t, in pounds per linear inch, neglecting the effect of the fore and aft curvature, can be shown to be approximately

$$t = 0.00087\ pa^2/c. \tag{17}$$

Values of t for various air pressures and bulging of the fabric are given in figure 6.

13. RIB LOADING AND STRESS.

The usual airplane rib may be considered as a beam supported at two points (at the spars) and sustaining the air force on all the fabric lying nearer to itself than to the neighboring ribs. In figure 7 is shown the distribution of the air force normal to the rib surface and also the distribution of the components of this air force normal to the chord. The running load on the rib is not sufficiently uniform to make applicable the ordinary formulas for uniformly loaded beams.

By considering the average loading upon each element of length as a concentrated load we may compute the shear and moment for a number of points and plot them as in figure 8. This process, however, is laborious.

For approximate treatment we may divide the rib into three parts, the segment between the spars, the front segment, and the rear segment, and consider the total running load on each segment as a concentrated load. The magnitude and position of each such load may be found by well-known methods. From these concentrated loads the shear and moment diagrams can be readily drawn, as shown in full line in figure 9, where the dotted lines are superposed from figure 8. The maximum vertical shearing forces are practically the same in both cases, while the maximum negative bending moment in the case of such approximation is about twice that of the true moment and should be halved for the working approximation.

If the concentrated load on the front and rear segments, as shown in figure 9, be denoted for each by R and located at a distance l from the spar, the unit bending stress next to the spar is

$$S = Rl/Z, \tag{18}$$

Z being the section modulus of the cross section of the unsevered part of the rib segment where it meets the spar.

Again, if R, the concentrated load on the portion of the rib amid spars, is distant a and b from the front and rear spars, respectively, the unit bending stress at R is

$$S = Rab/(a+b)Z, \tag{19}$$

Z being the section nodulus there. Dividing S in (19) by 2 gives a fair approximation to the true bending stress for the distributed load.

The rib shearing stress may be found by the shearing stress formulas presented in Part I.

Example 1.—A rib loaded as in figure 39 has the dimensions there specified; find the unit stresses for bending, maximum shearing, and average vertical shearing just outside the spars and just inside the spars; also the unit bending stress at R between the spars.

14. AILERON LOADING AND STRESSES.

The loads on the aileron are the control-wire pull and the air force. The normal pull may be taken as the greatest the pilot would care to exert regularly in flight and is measured with a spring balance when the pilot seated in a stationary machine vigorously plies the control. The aileron moment equals the control-wire pull times its distance from the aileron hinge axis; also equals the aileron air force times its distance from the hinge. If this latter distance be assumed of some reasonable magnitude and be divided into said moment, it gives the amount of the air force. Sometimes also the air force is estimated from the size, incidence, and forward speed of the aileron, taken with suitable aerodynamic data and with allowance for the propeller slip stream, if any. In practice, the aileron force may be assumed to be at the center of the surface and equal to PA, where P is the resultant pressure per unit area of the aileron surface A. The value of P is usually specified by the purchaser.

Having thus found either the control-wire pull or the moment of the air force on the aileron, the stresses may be readily computed from the frame diagram by the usual methods of statics. If the moment of the air force tends to twist the aileron's hinge rod, the unit stress in the latter is computed by the formula

$$S = M/Z \tag{20}$$

where M and Z are, respectively, the given moment and the torsion section modulus. In this case the aileron ribs are simple cantilevers jutting out from the hinge rod, and are stressed like the trailing edge of a wing plane, and are treated by the foregoing rib analysis.

Sometimes the control wire pulls on an aileron lever from whose outer end several stays run to the rear edge of the aileron surface, as shown in figure 38. Each principal aileron rib then sustains a compressive component force due to the applied stay, a transverse running air force, and the transverse component forces of its outer and its inner end attachments. If only the transverse forces be considered, the aileron rib stress may be calculated by the formula for the mid segment of a wing rib, as already treated. The endwise force causes, at any cross section of the aileron rib, a compressive unit stress roughly equal to that force divided by the section area.

The leading and trailing edges of the aileron are treated as continuous beams supported and loaded as in figure 13.

Example 2.—An aileron bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 38. Find the moment about the hinge and the stress in the control wire. Find also the vertical reactions at the stay wire upon the trailing edge beam.

15. RUNNING LOAD ON WING PLANES [1] AND SPARS.

The air loading and weight of a wing plane is in general not uniform along the whole length of the plane, but may be taken as uniform for each small unit of the length. The actual distribution of the air loading throughout the length, in a uniform wind,[2] is illustrated in figure 4. For

[1] In this text the term "wing" denotes a main supporting member on the right or left of the airplane. Thus, a biplane wing comprises two wing planes, the "top plane" and the "bottom plane," joined by "interplane" trussing. Similarly for a triplane, a quadruplane, a multiplane.

[2] In case a propeller slip stream washes the plane the wind is still less uniform over the plane. To be very accurate, this case would require special treatment.

practical computation this distribution may be taken as constant along each panel[1] or each spar length of the wing plane, and is so taken in the present treatment.

The manner of referring the running air load and running weight of the plane to the spars, and there resolving them in the plane of the lift trussing and drag trussing, is shown in figure 10. Let L,[2] D, W be the running lift, drag, and weight of the plane and al, bl the distances, respectively, of their points of application from the rear spar, a and b being numerical fractions and l the distance between spars. Then at the front spar the parallel components of L, D are aL, aD; and the parallel component of W is bW, which, taken from aL, gives the net running lift across wind at the spar in question. Compounding graphically this net lift, $aL-bW$, with the drag aD, gives the resultant spar running load R. This resultant is now resolved graphically into the components w_1, w_2 in the lift and drag truss planes; also into w, w^1 in the spar web plane and normal thereto.

In a similar manner the resultant running loads and their component running loads in the lift and drag truss planes may be found for the remaining spars. Frequently in practice the running load on the lower spar of a biplane is found from that of the upper by dividing by some simple ratio, say 1.2, as indicated by aerodynamic experiments.

Example 3.—A biplane wing has the form and loadings shown in figure 41; find the resultant loadings on the spars and their components in the planes of the lift and drag trussing for angles of incidence of 2° and 12°.

16. SPAR BENDING MOMENTS, SHEARS, PIN REACTIONS, DEFLECTIONS.

From the running load w_1 on a spar, figure 10, and from the position of the strut pins, or constraints, the bending moments, shearing forces, pin reactions, and deflections may be computed by the familiar formulas for loaded beams. In general, these four quantitaties can be computed by direct use of Clapeyron's original three-moment theorem, figure 11, but for usual cases are more conveniently found by the formulas derived therefrom and presented in figures 13, 14, 15, 16.

(*a*) *Bending moments and bending stresses.*—The bending moment diagram is usually a chain of parabolic curves, whose maxima are tabulated, for usual cases, in figures 13, 14, 15, 16. From these maxima and the tabulated joint moments the complete diagram is plotted, as in figure 17.

In some unusual cases the axes of the spar, strut, and stay do not pass through a common point. The increment of moment caused by such eccentricity of the stay attachment is treated analytically in figure 12 and applied graphically in figure 18.

The maximum bending moment in the strut plane, multiplied by w/w_1, gives that for the plane of the spar web, figure 10, from which may be computed the unit bending stresses in the spar. The unit stress is given by the equation

$$S = M/Z, \tag{21}$$

M being the moment and Z the section modulus of the cross section of the spar.

(*b*) *Shearing forces and shearing stresses.*—The shear diagram is drawn by plotting as ordinates the values of the transverse shearing force on each side of the pins, then joining the ordinates by straight lines, as shown in figure 17. Each line, as is well known, cuts the spar axis at a point of zero shear and of maximum moment.

The values of these shearing forces multiplied by w/w_1 give the shearing forces in the plane of the spar web, from which may be derived the corresponding shearing stresses by the shear formulas of Part I.

(*c*) *Pin reactions.*—From the two "vertical" shears at any spar joint the pin reaction is most readily found by simple subtraction as in figures 14, 15, 16. If the points of zero shear—that is, of maximum moment—are known, the pin reaction at any joint is taken as the distance between the neighboring maxima times the mean loading.

(*d*) *Deflection.*—To find the exact place and amount of the maximum spar panel bending the deflection curve may be plotted from the elastic equation given in figures 14, 15, 16.

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[1] The panel of a spar or wing plane is its portion between consecutive lift struts.

[2] The determination of L and D is explained in the aerodynamic treatment of airplanes.

Otherwise, since the point of maximum deflection in any span is near that of maximum bending moment, the latter point may be taken as the place of maximum deflection. Then the approximate maximum deflection d is, by the formula of figures 14, 15, 16,

$$d(=y) = -x_o[12\,M(l-x_o) + 4\,V(l^2+x_o^2) + w(l^3-x_o^3)]/24\,EI, \tag{22}$$

where x_o is the tabulated abscissa of the point of maximum moment. As shown for an extreme practical case in figure 19, the difference between this approximate deflection and the true deflection is less than 2 per cent.

Example 4.—Find the shears, moments, and reactions for the upper and lower front spars of the biplane trussing shown in figure 40 due to the uniform running loads found in example 3; also the reactions of the spars in the planes of the lift and drag trussing and the shears and moments on each spar in the plane of the spar web.

Example 5.—Find and plot the resultant moments due to the uniform loading and the eccentric stay wire attachments shown in figure 18.

Example 6.—Compute the deflections in the plane of the spar web for all panels of the biplane trussing of figure 40, using the results of example 4.

17. CONCENTRATED LIFT AND DRAG ON WING TRUSSING.

The total lift component on any strut pin in the plane of the lift struts is equal and opposite to the pin reactions given by the formulas of figures 14, 15, 16 for a running load in the plane of the lift trussing. Multiplying this lift component by w_2/w_1, figure 10, and adding half the air resistance of the adjoining strut and stay wires, gives the drag component on the strut pin in the plane of the drag struts. The pin lifts and drags so found are taken as the applied loads on the lift trussing and drag trussing and are used to find the endwise stresses in their struts, stays, and spars. Convenient formulas for the concentrated drag loads are given in figure 20.

An alternative method for finding the force on the strut pin is to multiply the mean running load on the spar by the distance between the points of zero shear in the adjoining spar panels. Equivalent formulas for this operation are given in figure 21.

In applying this alternative method, if the points of zero shear have not previously been found they may be taken as at the centers of each panel except the inner or root panel. For the root or inner panel the point of zero shear is three-eighths the panel length from the body hinge of the "engine section." This is an approximate method sometimes used for brevity. Its accuracy may be judged by reference to the typical moment diagram of figure 19.

To the above concentrated lifts must be geometrically added the weights of the struts and stays and in some cases the weight of the motor, the force of the aileron, the thrust of the propeller, etc.

When external stays are applied to the wing, such as lead wires or under struts, these may either be assumed severed or be taken as an integral part of the trussing. They are commonly assumed to be severed, so that the wing may be shown adequately strong without them and not liable to disaster in case of their accidental rupture. Then in turn the external stays are assumed to bear the whole lift or drag while the internal ones are severed.

If any sloping external stay, figure 24, of length r, whose three projections on the reference planes of the machine are x, y, z, sustain a tension R, whose components are X, Y, Z, then

$$R/r = X/x = Y/y = Z/z. \tag{23}$$

Thus if any internal drag wire should fail, causing a forward pull X in the lead wire, the stress in this latter would be $R=rX/x$, entailing a compression in the spar $Y=yX/x$.

In case of cabane stays, figure 24, the y may be zero and $R=rX/x$. Similarly, the stress in a fore-and-aft diagonal wing stay, supporting a drag X on the top plane, is $R=rX/x$.

Example 7.—Find the concentrated loads on the lift trussing of example 4, given the weight of the front struts, stays, cabanes, etc.

Example 8.—Given the resistance of the front struts and stays and the running load, find the concentrated loads on the drag trussing of example 4, by the zero shear method.

Example 9.—Given the resistance of the struts and stays at high and low speeds, find the concentrated loads on the drag trussings for both speeds, using values of the pin reactions found in example 4.

Example 10.—An aileron bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 38. Find the stresses in the stay wires.

18. ENDWISE STRESSES IN MEMBERS OF NONMULTIPLANE WING TRUSSING.

(*a*) *Due to lift and drag.*—From the given concentrated loads and frame diagram of the wing, the aggregate endwise stresses, and thence the unit stresses, are found by well known analytic and graphic methods.

Convenient analytical methods of finding the aggregate stresses, i. e., in struts, stays, and spars, are presented in figures 22 and 23. The usual graphic method is illustrated in figures 26 and 27.

If the stress in but a single strut or stay of a biplane be desired, it can be obtained directly by an appropriate formula as a simple summation, or a product following a summation. In such truss analysis the following generalizations may be useful:

1. Any strut exerts a thrust equal to the sum of all the loads preceding it. Thus in figure 22 R is preceded by the loads G, G', H, H', I, and therefore exerts at I a thrust equal to their sum.

2. Any stay exerts a tension equal to the sum of the loads preceding it times its own length divided by the truss gap.[1] Thus for the stay Q the tension is $(H+H'+I+I')\ q/h$. Otherwise the vertical component of any stay tension equals the difference between the strut thrust and the concentrated load on the strut joint; also the horizontal tension component equals the difference of the spar thrusts on either side of the joint.

3. Any top spar panel exerts a thrust equal to the sum of the moments of the preceding loads about its inner end divided by the gap. Any lower spar panel exerts a tension equal to the sum of the moments of the preceding loads about its outer end divided by the gap. The tension in a lower spar panel equals the compression in the one obliquely above and out from it.

(*b*) *Endwise stresses in struts, stays, and spars due to wing torsion.*—The aileron lift PA exerts a torsional moment $M=PAl$ about the wing axis distant l from PA. The ensuing endwise stresses in the wing struts, stays, and spars can be calculated by the formulas for a twisted pyramidal truss given in figures 33 and 34.

Example 11.—Find the endwise stresses in the struts, stays, and spars of the front lift trussing, figure 40, for low speed and the rear lift trussing for high speed.

Example 12.—Find the stresses in the drag trussings, figure 40, due to the concentrated loads of example 9.

Example 13.—Find the stresses and factors of safety in the spars, struts, and stays in figure 40 for low and high speeds, respectively.

Example 14.—Find the stresses in the principal members of the wing trussing of figure 40 due to a uniform air pressure of 20 pounds per square foot on the aileron surface of figure 38.

19. ENDWISE STRESSES IN MEMBERS OF MULTIPLANE WING TRUSSING.

Figure 25 gives a general process for finding the stresses in a multiplane wing truss, and applies it to a triplane. Before employing this method the total lift on the strut exerted by all the planes is found by summing their individual lifts, as in article 17 on concentrated loads.

20. STRESSES IN REDUNDANT TRUSS MEMBERS.

The last article illustrates the case of a truss having redundant members, whose stresses are indeterminate by rigid statics, but determinate by elastic statics. To generalize this case, suppose a multiplane wing truss having initial stresses in both its load wires and its landing

[1] "Truss gap" here means the distance between spar centers in either the lift or the drag plane.

wires. Here a lift L applied to a strut causes increase of tension in the load wires, decrease in the others. The increments of tension in both load and landing wires can be resolved vertically, summed and equated to the increment in L which causes them. The obvious expression for this is, by figure 25,

$$\Delta L = \Delta P m/p + \Delta P' m'/p' + \Delta Q n/q + \Delta Q^1 n^1/q'$$

in which the primes refer to the landing wires which cross the load wires diagonally. In many practical instances of wing and body construction the unprimed and primed quantities are respectively equal. The formula then becomes:

$$\Delta L = 2\ (\Delta P m/p + \Delta Q n/q)$$

Example 15.—Given the data for figure 25, as below, solve for the tensions in the stay wires; $L = 145$ pounds; $m = 60$ inches; $n = 50$ inches; $p = 99.8$ inches; $q = 94.2$ inches; $A = .012$ square inch; $B = .012$ square inch; and $E = 30{,}000{,}000$.

21. GROUPING OF WING ANALYSIS DATA AND COMPUTED VALUES.

Figure 28 [1] shows synoptically for a typical wing, (1) the general aerodynamic data for its individual planes, (2) the load distribution on the surfaces and trussing at both high and low speeds, and the stress analysis for these conditions, (3) the tabulated dimensions of the truss members, their principal stresses and factors of safety. Such detail calculations as do not appear in the diagram are given in the solutions of the individual problems of this chapter.

[1] This type of diagram, prepared by the writer, was published in part by the Franklin Institute Journal in December, 1914; entire in Aviation and Aeronautical Engineering in 1917.

REPORT NO. 82.

PART III.

AIRPLANE BODY STRESSES.

By A. F. ZAHM.

21. SCOPE OF TREATMENT.

The study of airplane body stresses may cover in succession: The tail unit; the tail skid; the chassis or landing carriage; the fuselage; each case compromising the applied loads, the induced reactions, the strength of the structural elements, and finally the factors of safety; the fuselage being treated last because stressed by all the other members thereto attached.

22. THE TAIL UNIT.

The tail unit comprises (*a*) the vertical tail surfaces; (*b*) the horizontal tail surfaces. The combined air forces on the tail surfaces—that is, the lateral force on the vertical surfaces and the vertical force on the horizontal surfaces—are taken as applied loads on the fuselage stern when in flight.

(*a*) *The vertical tail surfaces.*—The rudder may be hinged to the rear edge of a fixed vertical fin attached to the stern of the fuselage or other rearward projecting framework. The loads on the rudder are the air force and the tiller pull. In unbalanced rudders the normal tiller pull is usually taken as the greatest force a pilot would care to exert in regular flying, and is determined by measuring with a spring balance the force exerted by a pilot when seated in the stationary machine and plying the control vigorously. In common practice the force is assumed, as for the aileron in section 14, to be at the center of the surface and equal to PA, where P is the pressure per unit area of the rudder surface A.

The fixed vertical fin sustains both its own air force and the hinge forces exerted by the vertical rudder. The first may be taken as PA applied at the center of the fin area; the second may be computed by use of figure 13.

(*b*) *The horizontal tail surfaces.*—The horizontal rudder, or elevator, is usually hinged to the rear edge of a fixed tail plane, or stabilizer. The elevator stresses are found as for the cases already considered of the aileron and the vertical rudder. The stabilizer is treated very like a monoplane wing except that it sustains considerable force on its rear edge, due to the hinge pressures, and is aerodynamically influenced by the presence of the horizontal rudder, and commonly also by the propeller slip stream.

Example 1.—An elevator bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 37. Find the moment about the hinge and the stresses in the stays and the control wires; also the hinge reactions.

Example 2.—Find the vertical components of the pin reactions of the front and rear beams of the stabilizer or horizontal fin, figure 37, due to a uniformly distributed pressure of 20 pounds per square foot and the hinge reactions of example 1.

Example 3.—A rudder and vertical stabilizer bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 37; find the transverse loads on the upper and lower trussing of the fuselage and the transmitted couple about the normal axis of the various sections.

The tail skid.—When the craft is landing or resting on the earth the tail skid force is taken as a stern load on the fuselage.

The normal static or *dead load* on the tail skid is its ground pressure when resting on a level surface, or, in the case of certain waterplanes, it is the static lift on the rear float. The normal lift of the tail skid is $L = Wa/l$, figure 29, if W be the total weight of the craft, and a, l, the distances respectively of W and L from the tread, or forward support of the machine.

The *live load* on the tail skid may be resolved into rectangular components which are found as in figure 31, when the craft's dimensions and accelerations, there assumed, are known. Otherwise the maximum tail skid force to be provided against may be specified by the purchaser. From the force so found or specified the stresses in the tail skid, tail float or superstructure may be approximately calculated by elementary statics, ignoring the accelerations within the structure.

Example 4.—Compute the normal lift on the tail skid from the data given in figure 29.

Example 5.—Given $I=60{,}544$ pound-feet^2, $j_x=16$ feet/sec.^{2}, $j_y=8$ feet/sec.^{2}, $\alpha=0.1$ rad./sec.^{2}, in figure 31 and the dimensions of a machine, find the resultant live load on the tail skid.

23. UNDERCARRIAGE LOADS AND STRESSES.

The normal static or *dead load* at the bottom of the undercarriage equals in magnitude the total weight there supported when the craft is resting level. The supporting pressures are perfectly definite in some cases, as when the craft rests on two wheels and a skid, or on four cushioned wheels, etc.

The stresses in the under carriage may be computed first for the normal static load, then for a similar magnified load by multiplying by an assumed ratio, such as j/g in section 4.

When the airplane pitches, skids, or slews about, other considerations, which may be of great importance, enter the stress analysis. The case of an airplane skidding or abruptly canting is treated at the end of this article.

For a common airplane, figure 29, if l, a be, respectively, the distances aft the axle of the tail-skid toe and the weight W of the whole craft less wheels, then the upward pressure on the skid toe is Wa/l, and this taken from the weight gives twice the pressure R on each of the axles.

Resolving R parallel to the side-view projections of the struts, figure 29, gives, respectively, the force P sustained jointly by the front strut and stay and Q borne by the rear ones. These forces in turn resolved as shown give the stresses in the individual uprights of the undercarriage. The first resolution obviously gives

$$\begin{aligned} P &= R \sin \alpha / \sin \gamma \\ Q &= R \sin \beta / \sin \gamma, \end{aligned} \tag{24}$$

where α, β, γ are, respectively, the angles opposite P, Q, R in the force triangle. Similar equations in turn give the components of P, Q in the uprights.

The stresses in the undertrussing of a typical seaplane at rest are treated in figure 30. The lift R resolved parallel to the front view projections of the struts and stays, as shown, give its components P, Q in the planes, respectively, of the stays and of the struts. Now resolving P in the true plane of the stays, Q in that of the struts, as shown, gives the stresses in the uprights.

As shown in figure 29, the strut pairs bear down each with the force R on the axle, here assumed to be a straight and single tube. This axle normally finds support at the centers of the wheels and sustains on its segment outward from the struts bending and shearing stresses computable by the simplest cantilever formulas as used for wing ribs. Between the strut bearings the axle sustains a constant bending moment equal to the maximum in the cantilever portion. On this latter portion the maximum vertical shearing stress equals the wheel lift R; the maximum moment is Rl if l be the distance from the lift R to the down pressure of the strut pair. From the shear and moment the factors of safety are found as usual.

The *live load* on the bottom of the undercarriage is treated in quite the same manner as that on the tail skid by the equations of figure 31.

When an airplane skids on the ground or rests with one wheel low, the ground reaction on one wheel can be resolved into two rectangular components, one parallel the other perpendicular to the axis. The parallel component F, say, exerts on the axle a bending moment, $M=FR$, where R is the radius of the wheel. If W be the weight, α the angle of cant, $F=1/2\ W \sin \alpha$. The ensuing moment, $M=1/2\ WR \sin \alpha$, may be quite formidable.

Example 6.—From the data of figure 29 compute the normal load at the wheels of the undercarriage; also the stresses in the undercarriage struts and stays and their factors of safety.

Example 7.—Find the stresses in the undercarriage trussing of the seaplane in figure 30 due to a lift of 600 pounds applied at a point one-third the distance from the front to the rear strut attachments.

Example 8.—An airplane weighing 3,000 pounds, with wheels 2 feet in diameter and 6 feet apart, rests with one wheel 10 inches lower than the other. Find the added bending moment on the axle, assuming each wheel to bear half the entire weight.

24. FUSELAGE LOADS AND STRESSES.

The fuselage may sustain gravitational, aerodynamic, and impact or acceleration loads. The ensuing stresses at each point of the structure are separately computed, then combined to determine the resultant stress there. A twofold analysis is usually made, (*a*) for flying conditions, (*b*) for landing or static conditions. In both cases the analysis may be made either for the fuselage as a unit or separately for the rear segment, the front segment, and the center segment.

(*a*) *Fuselage loads and stresses for flying conditions.*—If the loads *exert no torque* on the fuselage, then for a typical *rear segment*, figure 32 presents the analytical treatment, figure 42 the graphical. In practical computation the weights of the struts, stays, and longeron panels are regarded as all concentrated on the upper pins, rather than as part on the upper, part on the lower pins. The air force on the side of the segment is comparatively negligible; that on the stern, due to the tail unit, is given in paragraph 2 of this part.

The gravitational stresses in the *front segment* are found similarly to those treated in (*a*); the power stresses, due to propeller thrust and torque, engine vibration, etc., may be estimated separately, then combined with the former. The aerodynamic forces on the bow are usually negligible.

The stresses in the *center segment* of the fuselage, due to the gravitational and aerodynamic loadings, may be found separately, then combined with those due to the action of the attached members; i. e., wings, undercarriage, and front and rear fuselage segments.

When the applied loads *exert a torque* on the fuselage, endwise stresses ensuing from the latter are computed by the formulas of figures 33 and 34 for twisted trusses. For example, if the rudder force PA is distant l from any axis of the fuselage, it may be replaced by a force PA and a couple PAl, both applied at said axis, the force generating one set of stresses, the couple another, and each set separately computable by one or the other of the above formulas.

(*b*) *Fuselage loads and stresses for landing or static conditions.*—For static conditions the loads inside the fuselage are the same as those for flight. The external applied loads are the wing weights, the reactions of the tail skid and undercarriage. The stresses are found as shown in figures 32 and 42.

For kinetic conditions the applied loads on each part are computed as explained in figure 31. The stresses are then found as explained in the preceding paragraph.

Example 9.—Find the stresses in the struts, stays, and longerons of the rear segment of the fuselage due to a uniform pressure of 20 pounds per square foot upon the horizontal tailpieces; also those due to gravitational loads alone.

Example 10.—Find the stresses in the struts, stays, and longerons of the vertical trussing of the front segment of the fuselage shown in figure 35, due to gravitational loads.

Example 11.—From the data in the problems above find the stresses and factors of safety for the principal members of the fuselage for a steady, circular flight around a level curve of 200 feet radius at 80 miles per hour.

Example 12.—Find the stresses in the rear segment of the fuselage due to the torsional loads in example 3.

25. GROUPING OF BODY ANALYSIS DATA AND COMPUTED VALUES.

Figures 35 and 36 show synoptically for a typical airplane body the graphical analysis and the numerical results for both flying and static conditions. Such detail calculations as do not appear in this diagram are given in the solutions of the individual problems of this part of the text.

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REPORT NO. 82.

PART IV.

PROBLEMS IN AIRPLANE STRESS ANALYSIS.

By L. H. Crook.

PROBLEMS IN PART I.

Stresses in Materials.

Example 1.[1]—If an accelerometer fixed to an airplane records a maximum vertical acceleration of 48 feet per second per second, what is the ratio of the abnormal to the normal loading? Given $g=32$ feet per second per second, $j=48$ feet per second per second.
Then by section 4

$$r=j/g=48/32=1.5 \text{ (ratio)}. \quad \text{Ans.}$$

Example 2.—An airplane in landing has a vertical velocity of 10 feet per second and a uniform cushion yield of 6 inches. Find the ratio of the abnormal to the normal stresses in the landing gear, assuming the machine to be a rigid structure.
Given $V=10$ feet per second.
Then by section 4

Velocity "head" $h=v^2/2g$
$=(10)^2/2(32)=1.56$ feet.

By equation 1

$r=1+h/d$
$=1+1.56/0.5=4.12$ (ratio). Ans.

Example 3.—Find the longitudinal shearing stress in a 4-inch square beam, given the total vertical shear as 1,400 pounds, first with diagonal vertical, then with it inclined 45°.

I. DIAGONAL VERTICAL.

Shear at neutral axis.
Given $a=8$ sq. ins.; $V=1{,}400$ lbs.; $I=21.33$ ins.[4]
$c=0.942$ ins.

By formula, 5

$S=ac\ V/I\,t$
$=8(0.942)1400/21.33(5.656)$
$=87.5$ lbs. per sq. in. Ans.

Shear at 1/4 h.[2]
Given $a=4.5$ sq. ins.; $V=1{,}400$ lbs.; $I=21.33$ ins.[4]
$c=1.414$ ins. $t=4.242$ ins.

$S=ac\ V/I\,t$
$=4.5(1.414)1400/21.33(4.242)$
$=98.3$ lbs. per sq. in. Ans.[3]

Shear at 1/2 h.
Given $a=2$ sq. ins.; $V=1{,}400$ lbs.; $I=21.33$ ins.[4]
$c=1.885$ ins. $t=2.828$ ins.

$S=ac\ V/I\,t$
$=2\ (1.885)1400/21.33(2.828)$
$=87.5$ lbs. per sq. ins.

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[1] Unless otherwise stated, all quantities are expressed in foot, pound, second, gravitational units.
[2] Distance from neutral axis to outermost fiber.
[3] Note that maximum shear is not at neutral axis.

Shear at 3/4 h.

$a = 0.50$ sq. ins.; $V = 1{,}400$ lbs.; $I = 21.33$ ins.^{4}
$c = 2.357$ ins. $t = 1.414$ ins.

$S = ac\ V/I\,t$
$= 0.50(2.357)(1400)/21.33(1.414)$
$= 54.7$ lbs. per sq. in. Ans.

Shear at outermost fiber.

Since $a = o$, $t = o$, then $S = o$. Ans.

II. DIAGONAL INCLINED 45°.

Shear at neutral axis.

Given $a = 8$ sq. ins.; $V = 1{,}400$ lbs.; $I = 21.33$ ins.^{4}
$c = 1$ in. $t = 4$ ins.

$S = ac\ V/I\,t.$
$= 8\ (1{,}400)/21.33(4)$
$= 131.2$ lbs. per sq. in. Ans.

Shear at 1/4 h.

Given $a = 6$ sq. in.; $V = 1{,}400$ lbs.; $I = 21.33$ ins.^{4}
$c = 1.25$ ins. $t = 4$ ins.

$S = ac\ V/I\,t.$
$= 6\ (1.25)\ 1{,}400/21.33(4)$
$= 123.1$ lbs. per sq. in. Ans.

Shear at 1/2 h.

Given $a = 4$ sq. ins.; $V = 1{,}400$ lbs.; $I = 21.33$ ins.^{4}
$c = 1.50$ ins.; $t = 4$ ins.

$S = ac\ V/I\,t$
$= 4\ (1.50)\ 1{,}400/21.33(4)$
$= 98.4$ lbs. per sq. in. Ans.

Shear at 3/4 h.

$a = 2$ sq. ins.; $V = 1{,}400$ lbs.; $I = 21.33$ ins.^{4}
$c = 1.75$ ins. $t = 4$ ins.

$S = ac\ V/I\,t$
$= 2\ (1.75)\ (1{,}400)/21.33(4)$
$= 57.4$ lbs. per sq. in. Ans.

hear at outermost fiber. $S = o$.

Example 4.—Find the resultant unit stress in a 2-inch square simple beam, 80 inches long; due to an endwise load of 900 pounds, a maximum bending moment of 1,100 inch-pounds and a maximum deflection of 0.05 inches at the place of maximum moment.

Given, $Z = 1.33$ ins.^{3}; $d = 0.05$ in.; $E = 1{,}500{,}000$.
$I = 1.33$ ins.^{4}; $A = 4$ sq. ins.

Then by footnote, section 7.

$$K = \sec.\ \frac{l}{2}\sqrt{P/EI}$$
$$= \sec.\ [40\sqrt{900/(1{,}500{,}000)\ (1.33)}]$$
$$= \sec.\ [.845] = 1.52.$$

Then by formula 7 and computed value of K

$S = P/A + M/Z + K\,P\,d/Z$
$= 900/4 + 1{,}100/1.33 + 1.52\ (900)\ (0.05)/1.33$
$= 225 + 827 + 51 = 1103$ lbs. per sq. in.

Example 5.—Find the unit stress in a pin-ended column 1 inch square and 30 inches long under an axial load of 200 pounds; also the unit stress when taking the eccentricity of the load as 2 inches.

Given $l=30$ ins.; $r=\sqrt{I/A}=0.288$ in.; $P=200$ lbs.
$A=1$ sq. in.; $a=4/3{,}000$

Then by formula 9.

$$S=[(1+a(l/r)^2]P/A$$
$$=[1+(4/3{,}000)\ (30/0.288)^2]\ 200/1$$
$$=3{,}081 \text{ lbs. per sq. in.}$$

Given $l=30$ ins.; $r=0.288$ (ins.); $c=1/2$ in
$A=1$ sq. in.; $a=4/300$ (constant)
$P=200$ lbs.; $p=2$ ins.

Then by formula 10.

$$S=[1+a(l/r)^2+cp/r^2)\ P/A$$
$$=[1+3/4{,}000\ (30/0.288)^2+0.5(2)/0.288^2]\ 200/1$$
$$=5{,}460 \text{ lbs. per sq. in.}$$

Example 6.—A beam is subject to a compressive unit stress of 200 pounds per square inch, and at the same time to a longitudinal shearing stress of 250 pounds per square inch. Compute the maximum resultant stresses.

Given, $S_s=250$ pounds per square inch. $S=200$ pounds per square inch.

Then by formulas 11 and 12

$$S_p=\sqrt{(S_s)^2+(S/2)^2}$$
$$=\sqrt{(250)^2+(200/2)^2}$$
$$=269 \text{ pounds per square inch. Ans.}$$
$$S_n=\sqrt{S/2\pm S_p}$$
$$=200/2+269=369 \text{ pounds per square inch. Ans.}$$

Example 7.—If a member whose allowable constant stress is 20,000 is stressed frequently to 15,000 and has an elastic limit of 60,000, what is the equivalent steady stress?

Given, $S=20{,}000$ pounds per square inch.
$n=1$ (constant).
$m=15{,}000/60{,}000=1/4$ (ratio).

Then by equation 13

$$S'=S(1+m)^n$$
$$=20{,}000\ (1+1/4)^1$$
$$=25{,}000 \text{ pounds per square inch. Ans.}$$

Example 8.—Find the maximum load for a pin-ended spruce column of length 60 inches, cross section 3 square inches, and moment of inertia 0.3 inch^4.

Given, $l=60$ inches; $l/r=60/0.31=193$ (slenderness ratio).
$A=3$ square inches; $E=1{,}500{,}000$ pounds per square inch.
$I=0.3$ inch.^{4}

Then by formula 15

$$P_{max}=\pi^2\ EI/l^2$$
$$=9.86\ (1{,}500{,}000)\ 0.3/(60)^2$$
$$=1{,}233 \text{ pounds. Ans.}$$

Example 9.—Find the factors of safety in example 6 for a maximum shearing stress of 1,000 pounds per square inch and a maximum compressive stress of 4,000 pounds per square inch; also the factor of safety in example 8 for an applied load of 250 pounds.
By section 10,

From example 6
Compressive stress = 369 pounds per square inch.
Shearing stress = 269 pounds per square inch.
Then, for compression
$F.\ S. = 4{,}000/369 = 10.8.$ Ans.
For shear
$F.\ S. = 1{,}000/269 = 3.7.$ Ans.

From example 8
Maximum load carried by beam = 1,250 pounds.
Then,
$F.\ S. = 1{,}250/250 = 5.$ Ans.

PROBLEMS IN PART II.

Airplane Wing Stresses.

Example 1.[1]—A rib loaded as in figure 39 has the dimensions there specified. Find the unit stresses for bending, maximum shearing, and average vertical shearing just outside the spars and just inside the spars; also the unit bending stress at R between the spars.

SECTION M.

(*a*) Consider the cap strips as carrying all the bending stresses.

Given $I = 1.22$ in.^{4}; $Z = 1.22/1.93 = 0.632$ in.^{3}
$R = 4$ lbs.; $l = 2$ in.

Then by formula (18)
$S = Rl/Z$
$= 4[2]/0.632 = 12.6$ lbs. per sq. in. Ans.

(*b*) Consider the cap strips and web as carrying the horizontal shearing stress.

Given $I = 2.01$ in.^{4}; $c = 1.0$ in.; $a = 0.61$
$t = 0.25$ in.; $V = 4$ lbs.

Then by formula (5) $S = ac\ V/It$
$= 0.61(1)4/2.01(0.25) = 4.9$ lbs. per sq. in. Ans.

(*c*) The total vertical shear at this section is not distributed as shearing stress over the web section, since the web of the rib ends at this section. The total vertical shear, however, is carried primarily by a compressive stress on the upper surface of the tongue that projects into the spar. The compressive stress in this case is

$S = V/A$
$= 4/(.25 \times .50) = 32$ lbs. per sq. in. Ans.

SECTION N.

(*a*) Consider the mid part of the rib as a simple beam.[2] The bending stress at section N is then zero.

(*b*) Consider the cap strips and web as carrying the horizontal shearing stresses.

Given $I = 2.36$ in.^{4}; $c = 1.08$ in.; $a = 0.64$ sq. in.
$t = 0.25$ $V = 12.22$ lbs.

[1] The solutions given in this example must be looked upon only as approximations. An accurate theoretical solution must take into account the hollowed web, the glued strips, strength of glued surfaces, etc.
[2] Spar being free to twist.

Then by formula (5)

$S = ac\ V/It$

$= 0.64(1.08)12.22/2.36(0.25)$

$= 7.76/0.59 = 13.1$ lbs. per sq. in. Ans.

(*c*) Treat the total shearing force as in (*c*) of section M.

SECTION O.

(*a*) Consider the bending stress S as carried by the actual section.

Given $I = 2.84$; $c = 2.30$; $a = 14.20$; $b = 19.80$; $R = 20.41$

$Z = I/c = 2.84/2.30 = 1.23$

Then by formula (19),

$S = R\ ab/2(a+b)z$

$= 20.41(14.20)(19.80)/2(34)(1.23) = 69$ lbs. per sq. in. Ans.

(*b*) Total vertical shear and also the horizontal shearing stresses are zero at this section.

SECTIONS P AND Q.

Treat similarly to section N and M, respectively.

Example 2.—An aileron bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 38. Find the moment about the hinge and the stress in the control wire. Find also the vertical reactions of the stay wire on the trailing edge beam.

(A) TOTAL LOAD ON AILERON.

By section 14 and figure 38.

Given $P = 20$ lbs. per sq. ft. (assumed loading).

A = area of aileron surface $= 20.7$ sq. ft.

Then total load $= P\ A$

$= 20 \times 20.7 = 414$ lbs. Ans.

(B) MOMENT ABOUT HINGE.

By figure 38. Center of gravity C $= 9.45''$ from hinge.

$M = CPA = 9.45(414) = 3{,}910$ lbs. in. Ans.

(C) STRESS IN CONTROL WIRE.

By figure 38, given arm $= 12.75$; moment $= 3{,}910$

Then tension $= 3{,}910/12.75 = 307$ lbs. Ans.

(D) VERTICAL REACTIONS OF TRAILING EDGE BEAM.

Total load distributed along trailing edge is approximately 1/2 aileron load.

By figures 38 and 13,

$2wl = 414/2 = 207$ lbs. and running load $= 207/162 = 1.28$ lbs. per linear in.

Given $l = 81$ in.; $b = 70$ in.; $a = 11$ in.

$w = 1.28$ lbs. per in.

By formula in figure 13—

$R_1 = w\ l\ (4\ l^2 - b^2)/8\ bl$

$= 1.28\ (81)\ [4(81)^2 - 70^2]/8(70)\ 81$

$= 48.8$ pounds. Ans.

$R_2 = 2\ (w\ l - R_1)$

$= 2\ [1.28\ (81) - 48.8] = 109.7$ pounds. Ans.

$R_3 = 48.8$ pounds. Ans.

Compare these answers with those found from the table in figure 13.

The vertical reactions are then as follows:

For central stay $= 109.7$ pounds. Ans.

Outside stays (each) $= 48.8$ pounds. Ans.

The tension in each stay wire may be found from these reactions. See example 10.

Example 3.—A biplane wing has the form and loadings shown in figure 41; find the resultant loadings on the spars and their components in the planes of the lift and drag trussings for angles of incidence of 2° and 12°.

The running lift L, the running drag D, and the distances to their points of application (al) depend upon the aerodynamic characteristics of the wing, the angle of incidence, the stagger, the biplane effect, etc. The running lift L and weight W as determined for any given wing plane of a machine are constant for all angles of incidence in straightaway flight. In the present example, however, L, D, W, a, and b are given.

I. ANALYSIS FOR LOW SPEED.

(Incidence 12°.)

(a) Running loads on upper front spar.

Given $L=2.256$ lbs./in $D=0.275$ lb./in. $W=0.313$ lb./in.
$a=0.67$ $a=0.67$ $b=0.46$

Then $aL=1.511$ lbs./in. $aD=0.184$ lb./in. $bW=0.144$ lbs./in.
$aL-bW=1.367$ lbs./in.

By simple graphics.

$w_1=1.389$ lbs./in. $w_2=0.100$ lb./in. $w=1.370$ lbs./in.

The running loads on lower front spar, upper rear spar, and lower rear spar are similarly found. Their values are given in the table below.

II. ANALYSIS FOR HIGH SPEED.

(Incidence 2°.)

(a) Running loads on upper front spar.

Given $L=2.256$ $D=0.141$ $W=0.313$.
$a=0.29$ $a=0.29$ $b=0.460$.

Then $aL=0.654$ $aD=0.041$ $bW=0.144$ $aL-bW=0.510$.

By graphics, $w_1=0.517$ $w_2=0.106$ $w=0.510$.

The running loads on lower front spar, upper rear spar, and lower rear spar are similarly found. Their values are given in the table below.

Grouping of data and computations for running loads w_1, w_2, w, on spars for low and high speeds.[1]

LOW SPEED.

Symbols.	L	D	W	a	b	aL	aD	bW	$aL-bW$	w_1	w_2	w
Front spars:												
Upper	2.256	0.275	0.313	0.67	0.46	1.511	0.184	0.144	1.367	1.389	0.100	1.370
Lower	1.845	.225	.286	.67	.46	1.236	.151	.131	1.105	1.127	.095	1.112
Rear spars:												
Upper	2.256	.275	.313	.33	.54	.744	.091	.169	.575	.588	.059	.580
Lower	1.845	.225	.286	.33	.54	.609	.074	.154	.455	.467	.049	.462
HIGH SPEED.												
Front spars:												
Upper	2.256	0.141	0.313	0.29	0.46	0.654	0.041	0.144	0.510	0.517	0.106	0.510
Lower	1.845	.116	.286	.29	.46	.535	.033	.132	.403	.408	.084	.403
Rear spars:												
Upper	2.256	.141	.313	.71	.54	1.602	.100	.169	1.433	1.456	.282	1.436
Lower	1.845	.116	.285	.71	.54	1.309	.082	.154	1.155	1.172	.226	1.158

[1] This method of grouping of data and computed values has been used; first, to help the computer in distinguishing the running loads and their components at the spars for different speeds; second, as a method of grouping of data and computed values for ready reference. The table below gives the computed values only.

Grouping of computed values of running loads on spars.

Speed—Plane o—	Low.						High.					
	Lift trussing.		Drag trussing.		Spar web.		Lift trussing.		Drag trussing.		Spar web.	
	Front.	Rear.	Front.	Rear.	Front.	Rear.	Front.	Rear.	Front.	Rear.	Front.	Rear.
Running load on upper spars	1.389	0.588	0.100	0.059	1.370	0.580	0.517	1.456	0.106	0.282	0.510	1.436
Running load on lower spars	1.127	.467	.095	.049	1.112	.462	.408	1.172	.084	.226	.403	1.158

Example 4.—Find the shears, moments, and reactions for the upper and lower front spars of the biplane trussing shown in figure 40, due to the uniform running loads found in example 3; also the reactions of the spars in the planes of the lift and drag trussing and the shears and moments on each spar in the plane of the spar web.

I. SHEARS, MOMENTS, REACTIONS FOR THE FRONT SPARS DUE TO RUNNING LOADS IN PLANE OF FRONT STRUTS (LOW SPEED).

1. *Upper wing spar.*—The upper wing spar is considered as a continuous beam supported at four points and having one overhanging end.

Given $A=B=C=D=1.389$ [1] lbs./ins.

$a=30$ ins.; $b=50$ ins.; $c=84$ ins.; $d=79$ ins.

Then by the formulas of figure 15.

Auxiliary Symbols.

$l=1.389[(50)^3+(84)^3]/4-1.389(30)^2 50/2$	[2] 217,970.21
$m=1.389[(84)^3+(79)^3]/4$	377,024.20
$h=2(50+84)$	268.00
$i=2(84+79)$	326.00

Joint Bending Moments.

$M_1=1.389(30)^2/2$	625.05
$M_2=[217970.21(326)-377024.20(84)]/268(326)-(84)^2$	490.44
$M_3=[217970.21-490.44(268)]/84$	1,030.14
$M_4=0$	0.00

Shear, Right of Pin.

$V_1=(490.44-625.05)/50-1.389(50)/2$	−37.41
$V_2=(1030.14-490.44)/84=1.389(84)/2$	−51.91
$V_3=(0-1030.14)/79-1.389(79)/2$	−67.89

Shear, Left of Pin.

$U_1=30(1.389)$	41.67
$U_2=-37.41+1.389(50)$	32.04
$U_3=-51.91+1.389(84)$	64.76
$U_4=-67.89+1.389(79)$	41.84

Pin Reactions.

$R_1=41.67+37.41$	79.08
$R_2=32.04+51.91$	83.95
$R_3=64.76+67.89$	132.65
$R_4=41.84+0$	41.84

Position of Maximum Moments.

$x_1=37.41/1.389$	26.93
$x_2=51.91/1.389$	37.37
$x_3=67.89/1.389$	48.87

Maximum Moments Between Joints.

$M'_1=625.05-(37.41)^2/2(1.389)$	+121.27
$M'_2=490.44-(51.91)^2/2(1.389)$	−479.55
$M'_3=1030.14-(67.89)^2/2(1.389)$	−628.98

2. *Lower wing spar.*—The lower wing spar is considered as a continuous beam supported at three points and having one overhanging end.

Given $A=B=C=1.127$ [3] lbs. per in.; $a=27$ ins.; $b=84$ ins.; $c=79$ ins.

Then by formulas of figure 14.

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[1] The running load may be taken as unity. In the present problem it is the running load in plane of front lift trussing for low speed. (See problem 3, Pt. II.)

[2] All calculations were carried out two decimal places to insure accuracy primarily for comparing other methods of calculation, as slide rule, graphical, etc. (See example 7, Pt. II, and fig. 18.)

[3] Running load on lower spar in plane of front lift trussing for low speed. (See example 3, Pt. II.)

Auxiliary Symbols.

$l=1.127[(84^3+79^3)/4]-1.127(27)^284/2$ 271,401.60
$h=2(84+79)$ 326.00

Joint Bending Moment.

$M_1=1.127\ (27)^2/2$ 410.79
$M_2=271401.60/326$ 832.52

Shears, Right of Section.

$V_1=(832.52-410.79)/84-1.127(84)/2$ ..... −42.31
$V_2=(0-832.52)/79-1.127(79)/2$ ..... −55.04

Shears, Left of Section.

$U_1=27(1.127)$ 30.42
$U_2=-42.32+1.127(84)$ 52.35
$U_3=-55.04+89.03$ 33.99

Pin Reactions.

$R_1=30.42+42.31$ 72.73
$R_2=52.35+55.04$ 107.39
$R_3=33.99+0$ 33.99

Position of Maximum Moments Between Joints.

$x_1=42.31/1.127$ 37.54
$x_2=55.04/1.127$ 48.83

Maximum Moments Between Joints.

$M'_1=410.79-(42.31)^2/2(1.127)$ ..... −383.41
$M'_1=832.52-(55.04)^2/2(1.127)$ ..... −511.49

II. REACTIONS OF SPARS IN PLANES OF LIFT AND DRAG TRUSSING FOR HIGH AND LOW SPEEDS.

The reactions in the planes of the lift and drag trussings for front and rear spars at high and low speeds may be found from the known reactions on the front upper and lower spars, by multiplying by the ratio of the running loads.[1] In the table below the ratios of the running loads are given, as well as the running loads.

Data and computed values for reactions.

Speed	Low.				High.			
Trussing	Lift.		Drag.		Lift.		Drag	
	Front.	Rear.	Front.	Rear.	Front.	Rear.	Front.	Rear.
Running load on upper spars	1.389	0.588	0.100	0.059	0.517	1.456	0.106	0.282
Ratio of loads	1	1.424	.072	.043	.373	1.049	.077	.204
Reactions of upper spars R_1	79.08	[1] 33.52	[1] 5.69	[1] 3.40	[1] 29.49	[1] 82.95	[1] 6.08	[1] 16.13
Reactions of upper spars R_2	83.95	35.59	6.04	3.60	31.31	88.06	6.46	17.12
Reactions of upper spars R_3	132.65	56.24	9.55	5.70	49.47	139.14	10.21	27.06
Reactions of upper spars R_4	41.84	17.74	3.01	1.79	15.60	43.89	3.22	8.53
Running load on lower spars	1.127	.469	.095	.049	.408	1.172	.084	.226
Ratio of loads	1	.416	.085	.044	.363	1.040	.075	.200
Reactions of lower spars R_1	72.73	30.25	6.18	3.20	26.40	75.63	5.45	14.54
Reactions of lower spars R_2	107.39	44.67	9.12	4.72	38.98	111.68	8.05	21.47
Reactions of lower spars R_3	33.99	14.13	2.88	1.49	12.33	35.34	2.54	6.79

[1] These values are found by multiplying the column on extreme left by the ratio of loads.

III. MOMENTS AND SHEARS IN PLANE OF SPAR WEB AS FOUND FROM THOSE IN PLANE OF LIFT TRUSSING FOR FRONT SPARS ONLY.

The shears and moments in plane of spar web may be found directly, by the equations of figures 14, 15, 16, etc.; using a running load in the plane of the spar web, or indirectly by ratio methods, that is, by ratio from a known analysis for unit loading or a running load in some other plane. The table below gives the moments and shears in plane of spar web as found from those in plane of lift trussing for front spars only.

[1] This is true only for similar spar lengths.

Data and computed values for moments and shears.

LOW SPEED.

Front spar	Upper.		Lower.	
Plane of	Lift trussing.	Spar web.	Lift trussing.	Spar web.
Running loads	1.389	1.370	1.127	1.112
Ratio of loads	1	.9864	1	.9867
Joint bending moments M_1	625.05	[1] 616.54	410.79	[1] 405.32
Joint bending moments M_2	490.44	483.77	832.52	821.44
Joint bending moments M_3	1,030.14	1,016.13	0	0
Joint bending moments M_4	0	0		
Maximum moments between joints M'_1	+121.27	+119.62	−383.41	−378.31
Maximum moments between joints M'_2	−479.55	−473.02	−511.49	−504.68
Maximum moments between joints M'_3	−628.98	−620.42		
Shears, left of pins U_1	41.67	41.10	30.42	30.01
Shears, left of pins U_2	32.04	31.60	52.35	51.65
Shears, left of pins U_3	64.76	63.87	33.99	33.63
Shears, left of pins U_4	41.84	41.27		
Shears, right of pins V_1	−37.41	−36.90	−42.31	−41.74
Shears, right of pins V_2	−51.91	−51.20	−55.04	−54.30
Shears, right of pins V_3	−67.89	−66.96		

[1] Found from column on left by using ratio of loads.

IV. MOMENTS AND SHEARS IN PLANE OF SPAR WEB FOR ALL SPARS AT HIGH AND LOW SPEED, AS FOUND FROM DATA IN TABLE III.

Moments and shears for spars.

UPPER SPARS.

Speeds	Low.		High.	
Spar	Front.	Rear.	Front.	Rear.
Running load	1.370	0.580	0.510	1.436
Ratio of loads	1	.424	.373	1.048
Joint-bending moments M_1	616.54	[1] 261.41	[1] 242.30	[1] 626.13
Joint-bending moments M_2	483.77	205.11	190.12	506.99
Joint-bending moments M_3	1,016.13	430.83	399.33	1,064.90
Joint-bending moments M_4	0	0	0	0
Maximum moments between joints M_1	+119.62	+50.71	+47.07	+125.36
Maximum moments between joints M_2	−473.02	−200.56	−185.89	−495.72
Maximum moments between joints M_3	−620.42	−263.05	−243.82	−650.20
Shears, left of pin U_1	41.10	17.42	16.15	43.07
Shears, left of pin U_2	31.60	13.39	12.41	33.11
Shears, left of pin U_3	63.87	27.08	25.10	66.93
Shears, left of pin U_4	41.27	17.49	16.21	43.25
Shears, right of pin V_1	−36.90	−15.64	−14.50	−38.67
Shears, right of pin V_2	−51.20	−21.70	−20.12	−53.65
Shears, right of pin V_3	−66.96	−28.39	−26.31	−70.17

[1] Found from column on left by using ratio of loads.

LOWER SPARS.

Speeds	Low.		High.	
Spar	Front.	Rear.	Front.	Rear.
Running load	1.112	0.462	0.403	1.158
Ratio of loads	1	.416	.363	1.042
Joint-bending moments M_1	405.37	168.61	147.13	422.34
Joint-bending moments M_2	821.44	341.71	124.04	855.94
Joint-bending moments M_3	0	0	0	0
Maximum moments between joints M_1	−378.31	−157.37	−57.12	−394.19
Maximum moments between joints M_2	−504.68	−209.94	−76.20	−525.87
Shears, left of pin U_1	30.01	12.48	4.53	31.27
Shears, left of pin U_2	51.65	21.48	7.79	53.81
Shears, left of pin U_3	33.63	12.99	5.07	35.04
Shears, right of pin V_1	−41.74	−17.36	−6.30	−43.49
Shears, right of pin V_2	−54.30	−22.58	−8.19	−56.58

A close examination of the foregoing results will show that the greatest stresses occur in the front spars for low speed and the rear spars for high speeds.

Example 5.—Find and plot the resultant moment due to the uniform loading and the eccentric stay wire attachments shown in figure 18.

I. GENERAL DATA.

$b = 50$ in.; $K_1 = 0$; $P = 0$
$c = 84$ in.; $K_2 = 0.023$; $Q = 228$
$d = 79$ in.; $K_3 = 0.025$; $R = 460$

II. COMPUTATIONS.

Consider the vertical components of the stay forces as concentrated loads on the continuous beam and apply the theorum of Bresse as given in figure 11 and explained in figure 12.

Application of Theorems to Spans (b) and (c).

$$M_1 b + 2M_2(b+c) + M_3 c = -Pb^2(K_1 - K_1^3) - Qc^2(2K_2 - 3K_2^2 + K_2^3)$$
$$0 + 2M_2(50+84) + 84M_3 = 0 - 228(84)^2(0.04628)$$
$$\therefore\ 268\ M_2 + 84\ M_3 = -74{,}453.78$$

Application of Theorems to Spans (c) and (d).

$$M_2 c + 2M_3(c+d) + M_4 d = -Qc^2(K_2 - K_2^3) - Rd^2(2K_3 - 3K_3^2 + K_3^3)$$
$$84\,M_2 + 2M_3(84+79) + o = -228(84)^2(0.024) - 460(79)^2(0.04812)$$
$$\therefore\ 84\,M_2 + 326\,M_3 = -176{,}756.21$$

By elimination

$$M_1 = 0;\ M_2 = -117;\ M_3 = -512;\ M_4 = 0$$

SHEARS AT RIGHT OF PINS.

$$V_1 = (M_2 - M_1)/b + P(1 - K_1)$$
$$= (-117 + o)/50 + 0 = -2.34.$$
$$V_2 = (M_3 - M_2)/c + Q(1 - K_2)$$
$$= (-512 + 117)/84 + 228(1 - 0.024) = +217.83.$$
$$V_3 = (M_4 - M_3)/d + R(1 - K_3)$$
$$= (o + 512)/79 + 460(1 - 0.025) = +454.98.$$

SHEARS AT LEFT OF PINS.

$$U_1 = o.$$
$$U_2 = V_1 - P$$
$$= -2.34 - o = -2.34.$$
$$U_3 = V_2 - Q$$
$$= +217.83 - 228 = -10.17.$$
$$U_4 = V_3 - R$$
$$= 454.98 - 460 = -5.02.$$

PIN REACTIONS.

$$R_1 = V_1 - U_1$$
$$= -2.34 - o = -2.34.$$
$$R_2 = V_2 - U_2$$
$$= +217.83 + 2.34 = +220.17.$$
$$R_3 = V_3 - U_3$$
$$= +454.98 + 10.17 = +465.15.$$
$$R_4 = V_4 - U_4$$
$$= +o + 5.02 = +5.02.$$

Check.

$$R_1 + R_2 + R_3 + R_4 = 688.$$
$$P + Q + R = 688.$$

MOMENTS AT POSITIONS OF LOADS.

$$M'_2 = M_2 + V_2 x$$
$$= -117 + 217.83(2) = +318.66.$$
$$M'_3 = M_3 + V_3 x$$
$$= -512 + 454.98(2) = +397.96.$$

III. GRAPHICAL RESULTS.

Figure 18 shows separately the moment curve for the uniformly loaded beam, that for the eccentric stay wires, and their resultant.

Example 6.—Complete the deflections in plane of spar web for all panels of the biplane trussing of figure 40, using the results of Table IV, example 4.

I. UPPER SPARS.

(1) Data table for use in computing deflections on front upper spar. (See Table IV, example 4, and formula for deflection in fig. 14.)

Span	*b.*	*c.*	*d.*
Joint-bending moments (M)	617	484	1,017
Shears, right of pin (V)	−37	−52	−67
Distance to maximum moment (x)	27	38	49
Length of span (l)	50	84	79
Running load (w)	1.370	1.370	1.370
Moment of inertia (I)	2.82	2.82	2.82
Modulus of elasticity (E)	1,880,000	1,880,000	1,880,000

(2) Computations.

The general formula for deflection, figure 14, is

$$d\ (=y) = -x[12\,M(l-x) + 4\,V\,(l^2-x^2) + w(l^3-x^3)]/24\,EI.$$

(*a*) Computation for span b:

$$(l-x) = 23 \quad (l^2-x^2) = 1{,}771 \quad (l^3-x^3) = 105{,}317.$$

$$d = -27\,[12(617)(23) - 4(37)(1{,}771) + 1.37(105{,}317)]/24(1{,}880{,}000)(2.82) = -0.0111.^1$$

(*b*) Computations for span c:

$$(l-x) = 46 \quad (l^2-x^2) = 5{,}612 \quad (l^3-x^3) = 537{,}832.$$

$$d = -38[12(484)46 - 4(52)5{,}612 + 1.37(537{,}832)]/127{,}283{,}400 = 0.048 \text{ inches.}$$

(*c*) Computations for span d:

$$(l-x) = 30 \quad (l^2-x^2) = 3{,}840 \quad (l^3-x^3) = 375{,}390.$$

$$d = -49[12(1{,}017)30 - 4(67)3{,}840 + 1.37(375{,}390)]/127{,}238{,}400 = 0.057 \text{ inches.}$$

(3) Computation [2] table for deflections in upper spars at high and low speeds as found from upper front spar at low speed.

UPPER SPARS.

Speeds	High.		Low.	
Spars	Front.	Rear.	Front.	Rear.
Ratio of running, load	1	0.424	0.373	1.048
Ratio of moments of inertia [3]	1	1.215	1	1.215
Product of ratios	1	.515	.373	1.273
Spans *b*	.011	[4].005	[4].004	[4].014
Spans *c*	.048	.024	.017	.061
Spans *d*	.057	.029	.021	.072

[1] Deflections usually turn out +; this is an exception.

[2] All deflections in the upper spars, assuming all upper spars to have the same spans, may be found from those computed for the front spar for a given speed and loading by a simple ratio. This ratio is directly dependent upon the ratio of the running loads and the inverse ratio of the moments of inertia, i. e., their product.

[3] Inverse ratio of moments of inertia.

[4] Found from values in first column by using ratio figure directly above.

(1) Data table for use in computing deflections on front lower spar:

LOWER SPARS.

Span	c.	d.
Joint-bending moments (M)	406	822
Shears, right of pin (v)	−42	−55
Distance to maximum moment (x)	38	49
Length of span (l)	84	79
Running load (w)	1.112	1.112
Moments of inertia (I)	2.82	2.82
Modulus of elasticity (E)	1,880,000	1,880,000

(2) Computations.

The general formula for deflection is

$$d(=y) = -x[12M(l-x) + 4V(l^2-x^2) + w(l^3-x^3)]/24EI$$

(a) Computation for span c:

$(l-x) = 46$; $(l^2-x^2) = 5{,}612$; $(l^3-x^3) = 537{,}832$

$d = -38[12(406)46 - 4(42)5{,}612 + 1.112(537{,}832)]/127{,}238{,}400 = 0.036$ inch

(b) Computations for span d:

$d = -49[12(822)30 - 4(55)3{,}840 + 1.112(375{,}390)]/127{,}238{,}400 = 0.051$ inch

(3) Computation table for deflections in lower spars at high and low speeds as found from lower front spar at low speed.

LOWER SPARS.

Speeds	High.		Low.	
Spars	Front.	Rear.	Front.	Rear.
Ratio of running loads	1	0.416	0.363	1.042
Ratio of moments of inertia	1	1.215	1	1.215
Product of ratios	1	.505	.363	1.266
Spans c	.036	.018	.013	.045
Spans d	.051	.025	.018	.064

Example 7.—Find the concentrated loads on the lift trussing of example 4, given the weight of the struts, stays, cabanes, etc.

I. PIN REACTION METHOD.

Computation table for concentrated loads on upper and lower pin joints as found in tables for spar reactions of example 4 and the given weights of attached struts, stays, wires, etc. (G′, H′, I′; G, H, I) are symbols for concentrated loads in figure 22.

FRONT UPPER PIN JOINTS.

Concentrated load symbol (fig. 22).	Beam reactions in plane of lift trussing.	Weights at pin joints.	Net load.	Practical working load.[1]
G′	79.08	0.55	78.53	79
H′	83.75	4.17	79.78	80
I′	132.65	4.22	128.43	129

FRONT LOWER PIN JOINTS.

G	0	0	0	0
H	72.73	4.72	68.01	69
I	107.39	4.77	102.62	103

REAR UPPER PIN JOINTS.

G′	82.95	0.55	82.40	83
H′	88.06	4.17	83.89	84
I′	139.14	4.22	134.92	135

REAR LOWER PIN JOINTS.

G	0	0	0	0
H	75.63	4.72	70.91	71
I	111.68	4.77	106.91	107

[1] See application in problem 11.

II. ZERO SHEAR METHOD.

The concentrated loads may also be found by a method similar to that used for the drag trussing in figure 21 and example 8; i. e., briefly, by multiplying the running loads by the distance between zero shears and subtracting the weights of struts and stays.

Example 8.—Given the resistance of the front struts and stays and the running load, find the concentrated loads on the drag trussing of example 4 by the zero shear method.

(*a*) Concentrated loads on upper front spar:

Given $A=B=C=D=0.100$ lb. per in.

$x_1=26.93$; $x_2=37.37$; $x_3=48.87$

$a=30$; $b=50$; $c=84$; $d=79$.

Then by formulas of figure 21,

$G=0.13+0.100(30)+0.100(26.93)=5.82$ [1]

$H=0.36+0.100(50-26.93)+0.100(37.37)=6.40$

$I=0.53+0.100(84-37)+0.100(48.87)=10.07$.

(*b*) Concentrated loads on rear upper spar:

Given $A=B=C=0.059$ lb. per in.

a, b, c, x_1, x_2, x_3 as above.

$G'=0.13+0.059(30)+0.059(26.93)=3.48$

$H'=0.36+0.059(50-26.93)+0.059(37.37)=3.92$

$I'=0.53+0.059(84-37.37)+0.059(48.87)=6.16$.

Example 9.—Given the resistance of the strut and stays at high and low speeds; find the concentrated loads on the drift trussings for both speeds, using values of the pin reactions found in example 4.

Computation table for concentrated loads on upper and lower drift trussings for low and high speeds.

LOW SPEED.

	Front spar.				Rear spar.			
	Load symbol.	Reaction.	Resistance.	Total.	Load symbol.	Reaction.	Resistance.	Total.
Upper drag trussing	G	5.69	0.13	[1] 5.82	G′	3.40	0.13	3.53
	H	6.04	.41	6.45	H′	3.60	.41	4.01
	I	.00	.00	.00	I′	.00	.00	.00
	J	9.55	.58	10.13	J′	5.70	.58	6.28
	K	.00	.00	.00	K′	.00	.00	.00
Lower drag trussing	G	6.18	.41	6.59	G′	3.20	.41	3.61
	H	.00	.00	.00	H′	.00	.00	.00
	I	9.12	.58	9.70	I′	4.72	.58	5.30
	J	.00	.00	.00	J′	.00	.00	.00

HIGH SPEED.

Upper drag trussing	G	6.08	0.37	6.45	G′	16.13	0.37	16.50
	H	6.46	1.18	7.64	H′	17.12	1.18	18.30
	I	.00	.00	.00	I′	.00	.00	.00
	J′	10.21	1.68	11.89	J′	27.06	1.68	28.74
	K	.00	.00	.00	K′	.00	.00	.00
Lower drag trussing	G	5.45	1.18	6.63	G′	14.54	1.18	15.72
	H	.00	.00	.00	H′	.00	.00	.00
	I	8.05	1.68	9.73	I′	21.47	1.68	23.15
	J	.00	.00	.00	K′	.00	.00	.00

[1] See application in example 12.

Example 10.—An aileron bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 38. Find the stresses in the stay wires.

I. BEAM REACTIONS.

The rear beam of the aileron is considered as continuous and supported by the stays at three points, with both ends overhanging. The vertical reactions of these stays have previously been found in example 2. Reactions as found in example 2.

$R_1=48.8$ lbs.; $R_2=109.7$ lbs.; $R_3=48.8$ lbs.

[1] Compare with more general solution in example 9.

II. TENSIONS IN STAYS.

The tensions in the three stay wires are found from the reactions above and the dimensions given in figure 38. By the formula of figure 24.

(*a*) For center stay:

Given $r=22.72$ ins.; $z=13.37$ ins.; $Z=109.7$.

Then by figure 24,

$$T_2=R=Zr/z=109.7(22.72)/13.37=186 \text{ lbs.}$$

(*b*) For each outer stay:

Given $r=61.78$; $z=13.37$; $Z=48.8$.

Then by figure 24,

$$T_1=T_2=R=Zr/z=48.8(61.78)/13.37=225 \text{ lbs.}$$

Example 11.—Find the endwise stresses in the struts, stays, and spars of the front lift trussing, figure 40 for low speed and the rear lift trussing for high speed.

I. STRESSES IN FRONT LIFT TRUSSING FOR LOW SPEED.

1. GENERAL DATA.[1]

$G=0$	$G'=79$	$b=50$	$p=80.3$
$H=69$	$H'=80$	$c=84$	$q=104.9$
$I=103$	$I'=129$	$d=79$	$r=100.9$
	$h=62.9$		

2. ANALYTICAL SOLUTION.

By figure 22:

Strut Stresses.

$$P=G$$
$$=O=0$$
$$Q=G+G'+H$$
$$=O+79+69=148.00$$
$$R=G+G'+H+H'+I$$
$$=O+79+69+80+103=331.00$$

Stay Stresses.

$$P'=p(G+G')/h$$
$$=80.3\ (0+79)/62.9=100.85$$
$$Q'=q(G+G'+H+H')/h$$
$$=104.9\ (0+79+69+80)/62.9=380.24$$
$$R'=r(G+G'+H+H'+I+I')/h$$
$$=100.9\ (0+79+69+80+103+129)/62.9=737.90$$

Spar Stresses.

$$P''=(G+G')b/h$$
$$=(0+79)\ 50/62.9=62.79$$
$$Q''=(G+G')(b+c)+c(H+H')/h$$
$$=(0+79)\ (50+84)+84(69+80)\ 62.9=367.28$$
$$R''=(G+G')\ (b+c+d)\ (c+d)\ (H+H')+d(I+I')/h$$
$$=(0+79)\ (50+84+79)+(84+79)(69+80)+79$$
$$(103+129)\ 62.9=945.02$$

A second method may be used to find the same values by using only the equation on the right of figure 22.

[1] See example 7.

Strut Stresses.

$P = G = 0.00$

$Q = P + G' + H$

$= 0 + 79 + 69 = 148.00$

$R = Q + H' + I$

$= 148 + 80 + 103 = 331.00$

Factors.

$n_1 = (P + G)/h$

$(0 + 79)/62.9 =$ [1] 1.255

$n_2 = (Q + H)/h$

$(148 + 80)\ 62.9 = 3.624$

$n_3 = (R + I)/h$

$(331 + 129)/62.9 = 7.313$

Stay Stresses.

$P' = pn_1$

$= 80.3(1.255) = 100.77$

$Q' = qn_2$

$= 104.9\ (3.624) = 380.15$

$R' = rn_3$

$= 100.9(7.313) = 737.88$

Spar Stresses.

$P'' = bn_1$

$= 50\ (1.254) = 62.70$

$Q'' = \mathrm{P} + cn_2$

$= 62.70 + 84(3.624) = 367.11$

$R'' = Q + dn_3$

$= 367.11 + 79\ (7.313) = 944.83$

3. GRAPHICAL SOLUTION.

The graphical solution is similar to that shown in figure 27.

II. STRESSES IN REAR LIFT TRUSSING FOR HIGH SPEED.

GENERAL DATA.

$G = 0$	$G' = 83$	$b = 50$	$p = 80.3$
$H = 71$	$H' = 84$	$c = 84$	$q = 104.9$
$I = 107$	$I' = 135$	$d = 79$	$r = 100.9$

$h = 62.9$

Solve as in I above. Results given in table below.

III. REFERENCE TABLE FOR STRESSES IN LIFT TRUSSINGS FOR HIGH AND LOW SPEEDS.

LOW SPEED.

Symbol.	Strut stresses.	Stay stresses.	Upper spar stresses.	Lower spar stresses.[2]
P	0	101	63	0
Q	148	381	368	63
R	331	738	946	368

HIGH SPEED.

P	0	106	66	0
Q	154	397	384	66
R	345	770	987	384

[1] Carry out three decimal places.

[2] Found from stresses in upper spar.

Example 12.—Find the stresses in the drag trussings figure 40, due to the concentrated loads of example 9.

I. STRESSES IN UPPER DRAG TRUSSING FOR LOW SPEED.[1]

GENERAL DATA.

$G'=3.53$	$G=5.82$	$b=50$	$p=60.4$
$H'=4.01$	$H=6.45$	$c=42$	$q=54.0$
$I'=.00$	$I=.00$	$d=42$	$r=54.0$
$J'=6.28$	$J=10.13$	$e=38.5$	$s=51.3$
$K'=.00$	$K=.00$	$f=38.5$	$t=51.3$
		$h=34$	

II. STRESSES IN LOWER DRAG TRUSSING FOR LOW SPEED.

GENERAL DATA.

$G=6.59$	$G'=3.61$	$b=42$	$p=54$
$H=.00$	$H'=.00$	$c=42$	$q=54$
$I=9.70$	$I'=5.30$	$d=38.5$	$r=51.3$
$J=.00$	$J'=.00$	$e=38.5$	$s=51.3$

III. STRESSES IN UPPER TRUSSING FOR HIGH SPEED.

GENERAL DATA.

$G=6.45$	$G'=16.50$	$b=50$	$p=60.4$
$H=7.64$	$H'=18.30$	$c=42$	$q=54$
$I=.00$	$I'=.00$	$d=42$	$r=54$
$J=11.89$	$J'=28.74$	$e=38.5$	$s=51.3$
$K=.00$	$K'=.00$	$f=38.5$	$t=51.3$

IV. STRESSES IN LOWER DRAG TRUSSING FOR HIGH SPEED.

GENERAL DATA.

$G=6.63$	$G'=15.72$	$b=42$	$p=54$
$H=.00$	$H'=.00$	$c=42$	$q=54$
$I=9.73$	$I'=23.15$	$d=38.5$	$r=51.3$
$J=.00$	$J'=.00$	$e=38.5$	$s=51.3$

Reference table for stresses in drag trusses for low and high speed.

STRESSES ON MEMBERS OF LOWER DRAG TRUSS.

Symbol.	Low speed.				High speed.			
	Struts.	Stays.	Rear spar.	Front spar.	Struts.	Stays.	Rear spar.	Front spar.
P	6.6	16.2	12.6	0	6.6	35.5	27.6	0
Q	10.2	16.2	25.2	12.6	22.4	35.5	55.2	27.6
R	19.9	38.0	53.7	25.2	32.1	83.3	117.7	55.2
S	25.2	38.0	82.2	53.7	55.2	83.3	180.2	117.7

STRESSES ON MEMBERS OF UPPER DRAG TRUSS.

P	5.8	16.6	13.8	0	6.5	40.8	33.8	0
Q	15.8	31.4	38.2	13.8	30.6	77.6	94.1	33.8
R	19.8	31.4	62.6	38.2	48.9	77.6	154.5	94.1
S	29.9	54.6	103.6	62.6	60.8	135.0	255.8	154.5
T	36.2	54.6	144.6	103.6	89.5	135.0	357.1	255.8

Example 13.—Find the stresses and factors of safety in the spars, struts, and stays shown in figure 40 for low and high speeds, respectively.

[1] The solutions for this example are similar to those in example 11. The arrangement of data for the different cases and tabulated results are given below.

1. GENERAL DATA.

Table I below gives the principal data, stresses, and factors of safety for the spars, struts, and stays. All other data required in the solution of this example may be found in the separate problems or in the diagrammatic form in figure 28.

TABLE I.

Symbol.[1]	Member.	Material.	Strength (pounds per square inch).	Section area (square inches).	Moment of inertia.	Section modulus.	For low speed.				For high speed.			
							Fiber stress (pounds per square inch).			Factor of safety.	Fiber stress (pounds per square inch).			Factor of safety.
							Bending.	Lift.	Drag.		Bending.	Lift.	Drag.	
Spars:														
A	Front spar	Spruce	4,300	2.63	2.82	1.88	±328	24	0	21.2				
B	do	do	4,300	2.63	2.82	1.88	±540	140	−15	10.2				
C	do	do	4,300	2.63	2.82	1.88	±540	360	−24	6.8				
D	do	do	13,000	2.63	2.82	1.88	±437	− 24	− 5	17.3				
E	do	do	13,000	2.63	2.82	1.88	±437	−140	−10	14.9				
F	Rear spar	do	4,300	3.26	2.32	1.16					±539	20	11	13.2
G	do	do	4,300	3.26	2.32	1.16					±918	118	48	6.4
H	do	do	4,300	3.26	2.32	1.16					±918	303	79	4.8
I	do	do	13,000	3.26	2.32	1.16					±738	− 20	17	10.6
J	do	do	13,000	3.26	2.32	1.16					±738	−118	36	10.0
			Strength, pounds.			*Length, inches.*		*Load, pounds.*				*Load, pounds.*		
Struts:														
K	Front	do	1,100	2.89	.279	6.29		148		7.4				
L	do	do	2,800	4.87	.792	6.29		331		8.4				
M	Rear	do	1,100	2.89	.279	6.29						154		7.1
N	do	do	2,800	4.87	.792							345		8.1
				Number of cables.	*Diameter.*									
Cables:														
O	Front	Steel	4,200	2	$\frac{1}{8}$			101		41.7				
P	do	do	6,400	2	$\frac{5}{32}$			381		16.8				
Q	do	do	6,400	2	$\frac{3}{16}$			738		8.6				
R	Rear	do	4,200	2	$\frac{1}{8}$							106		39.6
S	do	do	6,400	2	$\frac{5}{32}$							397		16.1
T	do	do	6,400	2	$\frac{3}{16}$							770		8.3

Factors of safety are given for points of greatest resultant tensile or compressive stress.

2. SOLUTION FOR SPARS.

TABLE II.—*Values of the bending moments* (±), *the tensions* (−), *and compressions* (+) *on each spar at the points marked "X" in fig. 28.*

FOR LOW SPEED.

Symbol.	Bending moment.	Load due to lift truss.	Load due to drag truss.
	Inch-pounds.	*Pounds.*	*Pounds.*
A	± 617	+ 63	0
B	±1,016	+368	−38.2
C	±1,016	+945	−62.6
D	± 822	− 63	−12.6
E	± 822	−368	−25.2

FOR HIGH SPEED.

F	± 626	66	33.8
G	±1,065	384	154.5
H	±1,065	987	255.8
I	± 856	− 66	55.2
J	± 856	−384	117.7

[1] The values above may be found in examples 4, 11, 12, or in figure 28 in diagrammatic form.

TABLE III.—*Computations for resultant fiber stresses for low speed.*[1]

LOW SPEED (COMPRESSIVE STRESSES).

Member.	Bending stress compression. $S_b = M/Z$	Equivalent compressive stress due to bending. $NS_b = \frac{4,300}{7,900} S_b$	Compressive stress. $Sc.$	Resultant compressive stress. $S = S_c + \frac{4,300}{7,900} S_b$
A	[2] 328	178	24	202
B	540	294	125	419
C	540	294	336	630

LOW SPEED (TENSILE STRESSES).

Member.	Bending stress tension. $S_b = M/Z$	Equivalent tensile stress due to bending. $NS_b = \frac{13,000}{7,900} S_b$	Tensile stress. $St.$	Resultant tensile stress. $S = S_t + \frac{13,000}{7,900} S_b$
D	−437	−719	− 29	−748
E	−437	−719	−150	−869

[1] Spars A, B, C, D, E have the lowest factors of safety for low speed.
[2] An additional bending stress due to deflection is sometimes added to this stress.

Example for member A in table above. (See Tables I and II.)

$S_b = M/Z$

$= 617/1.88 = 328$ lbs. per sq. in.

Equivalent compressive stress due to bending (see section 7 and formula 8).

$NS_b = 4,300(328)/7,900 = 178$ lbs. per sq. in.

Compressive stress S_c is the resultant compressive stress as found from columns two and three, Table II, and cross-sectional area, Table I.

$$S_c = 63/2.63 = 24 \text{ pounds per square inch.}$$

Resultant compressive stress. (Add columns 2 and 3 above.)

$$S = S_c + 4,300(S_b)/7,900.$$
$$= 24 + 178 = 202 \text{ pounds per square inch.}$$

This value is then used to determine the factor of safety. Compressive strength is 4,300 pounds per square inch.

$$\text{Factor of safety} = 4,300/202 = 21.2.$$

TABLE IV.—*Computations for resultant fiber stresses for high speed.*[1]

HIGH SPEED (COMPRESSIVE STRESSES).

Member.	Bending stress compression, $S_b = M/Z$.	Equivalent compressive stress due to bending, $NS_b = \frac{4,300}{7,900} S_b$.	Compressive stress, S_c.	Resultant compressive stress, $S = S_c + \frac{4,300}{7,900} S_b$.
F	539	294	31	325
G	918	499	166	665
H	918	499	382	881

HIGH SPEED (TENSILE STRESS).

Member.	Bending stress tension, $S_b = M/Z$.	Equivalent tensile stress due to bending, $NS_b = \frac{13,000}{7,900} S_{bt}$.	Compressive tensile stress, S_t.	Resultant tensile stress, $S = S_t + \frac{13,000}{7,900} S_b$.
I	−378	−1,214	− 3	−1,217
J	−738	−1,214	−82	−1,296

[1] Spars *F*, *G*, *H*, *I*, *J* have usually the lowest factors of safety for high speed.

Example for member I in table above:

$$S_b = M/Z.$$
$$= 856/1.16 = 738 \text{ pounds per square inch.}$$

Equivalent tensile stress due to bending.

$$NS_b = 13{,}000\ S_b/7{,}900.$$
$$= 13{,}000(738)/7{,}900 = 1{,}214 \text{ pounds per square inch.}$$

Tensile stress S_t is the resultant tensile stress as found from columns 2 and 3, Table III, and cross-question area in Table I.

$$S_t = -10.8/3.26 = -3 \text{ pounds per square inch.}$$

Resultant tensile stress (add columns 2 and 3).

$$S = S_t\ 13{,}000\ S_b/7{,}900.$$
$$= -3 - 1{,}214 = -1{,}217 \text{ pounds per square inch.}$$

This value of stress is used in determining the factors of safety:

$$\text{Factor of safety} = 13{,}000/1{,}217 = 10.6. \quad \text{Ans.}$$

3. SOLUTION FOR STRUTS.

The data for the struts with the resultant loads upon them are given in Table I. The value for strength of struts is best found by actual test, in the case of design they are computed. In the table above it is the actual strength by test. The loading is taken from the lift truss diagram in figure 28 or from example 11. The factor of safety is found in the usual manner.

4. SOLUTIONS FOR CABLES OR STAYS.

The same analysis applies to cables as to struts. The strength of the cables is usually known from tests made by the manufacturer.

Example 14.—Find the stresses in the principal members of the wing trussing in figure 40 due to a uniform air pressure of 20 pounds per square foot on the aileron surface in figure 38.

1. GENERAL DATA.

(*a*) Eccentric load = 414 pounds; eccentricity = 9.45 + 17.
(*b*) Torque at each station = 414 × 26.45 = 10,950 in./lbs.
(*c*) Lengths of stays S, T, U, V. (See fig. 34.)

First panel.				Second panel.			
S_1	T_1	U_1	V_1	S_2	T_2	U_2	V_2
90.6	104.9	90.6	104.9	86	101	86	101

(*d*) Computation tables for direction cosines.

Symbol.	l	X	Y	Z	Direction cosines.		
					S_x	S_y	S_z
S_1	90.6	−84	0	−62.9	−0.927	0	+0.694
S_2	86.0	−79	0	−62.9	− .918	0	+ .731

Symbol.	l	X	Y	Z	Direction cosines.		
					t_x	t_y	t_z
T_1	104.9	−84	−34	0	−0.801	−0.324	0
T_2	101.0	−79	−34	0	− .782	− .336	0

Symbol.	l	X	Y	Z	Direction cosines.		
					u_x	u_y	u_z
U_1	90.6	−84	0	+62.9	−0.927	0	+0.694
U_2	86.0	−79	0	+62.9	− .918	0	+ .731

Symbol.	l	X	Y	Z	Direction cosines.		
					V_x	V_y	V_z
V_1	104.9	−84	34	0	−0.801	0.324	0
V_2	101.0	−79	34	0	− .782	.336	0

2. SOLUTION.

(*a*) Stresses in stays transmitting torque forces from station No. 1 to station No. 2. Given (see fig. 34):

$l = 35.8$ ins.; $a = 34$ ins.; $b = 62.9$ ins.

Torque = 10,950 in./lbs.

Then by formulas of figure 34:

R = Torque $/4l$

$= 10{,}950/4(35.8)$ 76.4

$P = Rb/2l$

$= 76.466\ (62.9)/2(35.8)$ 67.2

$Q = Ra/2l$

$= 76.466\ (34)/2(35.8)$ 36.3

Since this problem comes under special case I, right prismatic truss, then, the general equations of figure 34 reduces to

$$t_y T = -2P \qquad s_x S + S' = 0$$
$$u_z U = +2Q \qquad t_x T + T' = 0$$
$$v_y V = +2P \qquad u_x U + U' = 0$$
$$s_z S = +2Q \qquad v_x V + V' = 0$$

Solution is then

1. $T_1 = -2P/t_y$.

   $T_1 = -2(67.2)/(-0.324)$ 414.9

2. $U_1 = +2Q/u_z$.

   $U_1 = +2(36.3)/(0.694)$ 104.6

3. $V_1 = -2P/v_y$.

   $V_1 = -2(67.2)/(-0.324)$ 414.9

4. $S_1 = +2Q/s_z$.

   $S_1 = +2(36.3)/(0.694)$ 104.6

(*b*) Stresses in stays transmitting torque forces from station No. 2 to station No. 3. The values of l, a, b, P, and Q are the same as in the first panel.

1. $T_2 = -2P/t_y$
   $T_2 = -2(67.2)/(-0.336)$ 400.0
2. $U_2 = +2Q/u_z$
   $U_2 = +2(36.3)/(0.731)$ 99.3
3. $V_2 = -2P/v_y$
   $V_2 = -2(67.2)/(-0.336)$ 400.0
4. $S_2 = +2Q/s_z$
   $S_2 = +2(36.3)/(0.731)$ 99.3

Example 15.—Given the data for figure 25, as below, solve for the tensions in the stay wires; $L = 145$ lbs.; $m = 60$ in.; $n = 50$ in.; $p = 99.8$ in. $q = 94.2$ in.; $A = 0.012$ sq. in.; $B = 0.012$ sq. in.; $E = 30{,}000{,}000$.

DATA.

$L = 145$ lbs.; $m = 60$ in.; $n = 50$ in.
$p = 99.8$ in.; $q = 94.2$ in.
$A = 0.012$ sq. in.; $B = 0.012$ sq. in.; $E = 30{,}000{,}000$.

SOLUTION.

By formulas in figure 25:

$P = LAmq^2/(Am^2q^2/p + Bn^2p^2/q)$
$P = [145(0.012)60(94.2)^2]/[(0.012)(60)^2(94.2)^2/99.8 + 0.012(50^2)(99.8)^2/94.2] = 132.1$ lbs.
$Q = LBnp^2/(Am^2q^2/p + Bn^2p^2/q)$
$= 145(0.012)50(99.8)^2/[\text{constant}]$ [1] $= 123.6$ lbs.

PROBLEMS IN PART III.

Airplane Body Stresses.

Example 1.—An elevator bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 37. Find the moment about the hinge and the stresses in stays and the control wires; also the hinge reactions.

(A) MOMENT ABOUT HINGE.

The moment about the hinge is equal to the product of the area, the uniform pressure, and the distance from the hinge axis to the centroid.
Given $A = 11$ square feet.; $P = 20$ pounds per square foot.
Distance to centroid = 15 in.
Then moment = $11(20)15 = 3{,}300$ inch-pounds.

(B) TENSION IN CONTROL WIRE.

The control wire pull times its distance from the hinge axis is equal to the moment in (*a*) above.
Tension in control wire = $3{,}300/7.75 = 425.8$ pounds.

(C) TENSION IN STAY WIRES.

The vertical reactions of the stays are approximately equal to one-half the total load on the elevator. Consider the stays as attached to a flexible rib, forming a continuous beam on three supports.

Then by table in figure 13, given $A \times P = 220$ pounds.; $b/l = 1$.

$wl = 220/4 = 55$ pounds.
$R_1 = R_3 = 0.375(55) = 20.62$ pounds.
$R_2 = 1.25(55) = 68.75$ pounds.
Check $R_1 + R_2 + R_3 = 110$ pounds.

[1] Use denominator as found directly above.

From these reactions may be found the tensions in the stay wires by a treatment similar to that used to find the tensions in aileron stays. (See example 10, Pt. II.)

(D) HINGE REACTIONS.

The vertical hinge reactions may be considered as due to a uniformly loaded beam supported at three points and bearing one-half the total load on the elevator. The reactions are approximately equal to those found in (*c*) above. To the middle reaction must be added the vertical reaction of the mast, which is equal to the total vertical reactions of the stays, or one-half the total load on the elevator, plus the vertical component of the control wire pull.

Control wire pull.

Given $R=425.80$ pounds.; $z=7.25$ inches; $r=42.75$ inches.

Then component of control wire pull

$Z=Rz/r=425.80(7.75)/42.75=72.21$ pounds.

Hinge reactions

$R_1=20.62$
$R_2=68.75+110+72.21=250.96$
$R_3=20.62$.

Example 2.—Find the vertical components of the pin reactions of the front and rear beams of the stabilizer or horizontal fin, figure 37, due to a uniformly distributed pressure of 20 pounds per square foot and the hinge reactions of example 1.

(A) TOTAL LOAD EQUALS THE UNIT PRESSURE TIMES THE AREA.

Given, $B=28.70$ square feet; $P=20$ pounds per square foot.
Then, total load $=28.70\ (20)=574$ pounds.

(B) DISTRIBUTION OF LOADING ON RIBS AND BEAMS.

The ribs may be considered as beams supported at two points (the position of front and rear beams, see *m* and *n* in figure 37). Approximately 0.75 *W* and 0.25 *W* is carried by the front and rear beams, respectively.

Front beam, $0.750(574)=430.50$ pounds.
Rear beam, $0.250(574)=143.50$ pounds.

(C) PIN REACTIONS DUE TO THE LOAD ON THE FRONT BEAM.

Consider as a continuous beam supported at three points and having both ends overhanging.

By table in figure 13 $W=wl=430.50/2=215.20$

$b/l=28/50 = 0.56$

Then
$R_1=0.822\ W=177.11$
$R_2=0.354\ W=\ 76.28$
$R_3=0.822\ W=177.11$

Sum $=430.50$

(D) PIN REACTIONS ON REAR BEAM.

Consider the rear beam as a continuous beam supported at the stern post and two stays

By figure 13, given $W=wl=143.50/2=71.75$

$b/l=\ 28/56\ =\ 0.50$

Then
$R_1=0.927(71.75)=67.23$
$R_2=0.126(71.75)=\ 9.04$
$R_3=0.937(71.75)=67.23$

Sum $=143\ 50$

The total vertical hinge reactions of the rudders found in example 1 must be added to the reactions R_1 and R_2. The true pin reactions of the rear beam of the horizontal stabilizer then become:

$$R_1 = 67.23 - 292.20 = 359.43$$
$$R_2 = 9.04 - 0 = 9.04$$
$$R_3 = 67.23 - 292.20 = 359.43$$
$$\text{Sum} = 727.90$$

The sum of all the vertical reactions of the stabilizer minus the vertical components of the stay wire pulls should equal the total load on stabilizer and elevator.

Reactions of front beam	430.50
Reactions of rear beam	727.90
Sum,	1,158.40
Minus vertical components of stay wires,	144.42
	1,013.98

Again, Total load on stabilizer = 574 pounds.
Load on left elevator = 220 pounds.
Load on right elevator = 220 pounds.

1,014

Example 3.—A rudder and vertical stabilizer bearing a uniform pressure of 20 pounds per square foot has the dimensions and structural form shown in figure 37; find the transverse loads on the upper and lower trussings of the fuselage in figure 36 and the applied couple about the normal axis of its various sections.

1. GENERAL DATA.

Member.	Area.	Centroid.	
		[1] $\bar{z}$.	[1] $\bar{x}$.
Rudder	12.00	−17	19
Stabilizer	3.80	13	10
Rudder and stabilizer	15.80	− 9	17
Length of stern post, 12 inches.			

[1] $\bar{z}$ is the distance (positive upward) from axis of upper longeron and $\bar{x}$ is the distance (positive forward) from axis of stern post.

2. WIND FORCE.

On rudder $= PA = (20)\ (12) = 240$ pounds.
On stabilizer $= PA = (20)\ (3.80) = 76$ pounds.

Total, 316 pounds.

3. TRANSVERSE LOADS ON HORIZONTAL TRUSSING AND COUPLES AT VARIOUS SECTIONS.

The total load at the centroid of the rudder and stabilizer may be replaced by an equal load at the center of the stern post and an equivalent couple.

Then,

(*a*) Load at center of stern post = 316 pounds.
(*b*) Couple in vertical plane of stern post 316 (17 + 6) = 7,268 pounds per sq. in.

(*c*) The couples at the various sections may be conveniently arranged in the following table. (See fig. 36 for dimensions of members.)

Station No.	Transverse load.	Eccentricity.[1]	Torque L (couple).
1	316	23	7,268
2	316	24.5	7,742
3	316	26	8,216
4	316	27.7	8,753
5	316	29.6	9,354
6	316	31.5	9,954
7	316	33.1	10,459

Computations for stresses due to the applied couples alone are given in example 12.

[1] Vertical distance of load above axis of sections.

Example 4.—Compute the normal lift on the tail skid from the data given in figure 29. Given $W=1{,}890$ lbs.; $a=19.13$ ins.; $l=205.8$ ins.

$$L=Wa/l$$
$$=1{,}890(19.13)/205.8$$
$$=175.6 \text{ lbs.}$$

Example 5[1].—Given $I=60{,}544$ lb.$-$ft.^{2}, $j_x=16$ ft./sec.^{2}, $j_y=8$ ft./sec.^{2}, $\alpha=0.1$ rad./sec.^{2} in figure 31 and the dimensions of a machine, find the resultant live load on the tail skid.

Given $M=1{,}890$ lbs. $\quad j_x=16$ ft./sec.^{2} $\quad \bar{x}=1.59$ ft.
$I=60{,}544$ lb.$-$ft.^{2} $\quad j_y=8$ ft./sec.^{2} $\quad \bar{y}=2.91$ ft.
$\alpha=0.1$ rad./sec.^{2} $\quad \beta=3^\circ\ 37'$
$p=17.14$ ft. $\quad g=32$ ft./sec.^{2}

Then, by figure 31,

$$P_y=\{M[j_y\bar{x}-j_x\bar{y}+g\ cos\ \beta.\bar{x}]+1_o\alpha\}/p.$$
$$P_y=\{1890[8(1.59)-16(2.91)+32(.998)(1.59)]+60{,}544(.1)\}/17.14.$$
$$P_y=2{,}221 \text{ poundals, or } 69.4 \text{ pounds of force.}$$

Example 6.—From the data in figure 29 compute the normal load at the wheels of the undercarriage; also the stresses in the struts and stays and their factors of safety.

1. LOAD ON WHEELS.

Load carried by each wheel $=857$.[2]

2. STRESSES IN STRUTS AND STAYS (ANALYTICAL).

Applying formula 24 to the triangles A, B, C in figure 29, we have—

(*a*) For component in plane of front trussing,

$$P=R \sin \alpha/\sin \gamma$$
$$=857 \sin (68°23')/\sin (76°14')$$
$$=820.5.$$

In a similar manner the stresses are found.

(*b*) For component in plane of rear trussing	511.0
(*c*) For tension in front stay	619.7
(*d*) For compression in the front strut	1,307.1
(*e*) For tension in rear stay	301.7
(*f*) For compression in rear strut	778.9

3. STRESSES IN STRUTS AND STAYS (GRAPHICAL).

The graphical solutions are shown in figure 29. Figure 29 shows the lift components in planes of front and rear trussings, both being in a plane normal to axle. From these components the stresses in the front and rear struts and stays are found by simple graphics as shown.

[1] Solved by using absolute F. P. S. units. [2] Total weight of machine minus load on tail skid and weights of wheels and axle.

4. FACTORS OF SAFETY.

The factors of safety are found by dividing the standard strength in pounds by the load in pounds.

The table below gives the complete data and results.

Member.		Material.	Standard strength.	Section area.	Moment of inertia.	Length in inches.	Load in pounds	Stress in pounds per square inch.	Factor of safety.
Struts	front	Spruce	5,600	.....	0.418	33.3	1,307	.....	4.2
	rear	do	1,990	.....	.418	55.7	779	.....	2.5
Stays	front	Cable	4,700	$1\frac{3}{16}$	.....	.....	−620	.....	7.5
	rear	do	4,700	$1\frac{3}{16}$	.....	.....	−302	.....	15.5

[1] Inches in diameter.

Example 7.—Find the stresses in the undercarriage trussing of the seaplane in figure 30, due to a lift of 600 pounds, applied at a point one-third the distance from the front to the rear strut attachments.

The resultant force is resolved along three axes, passing through its point of application; the X axis, which in the present case may be conveniently taken parallel to the line of the fore-and-aft lower pin connections of the trussing to the pontoon; the Y and Z axes normal thereto. The stresses in the trussings are then determined separately for each component and then algebraically added.

1. STRESSES DUE TO THE Z COMPONENT.

The Z component in the present problem acts in a vertical plane through the fore-and-aft pin connections of the trussing.[1] This vertical load is resolved, as shown in figure 30, into components in the planes of the fore-and-aft side struts and fore-and-aft stays, both components being in the YZ plane. From each of these components the stresses in the stays and struts may be found as shown. The component in the plane of the stays causes a drag in the strut plane, which must be determined before solving for the strut plane stresses. These drag forces (see forces (169) and (24) in diagram for true plane of struts, figure 30) are caused by the tension in the stays. Figure 30 (A) shows the resolution of lift on vertical plane (YZ); B, the diagram for the lengths and distances in true plane of stays with the graphical solution for stresses and strut reactions; (c), diagram for true plane of struts and graphical solution for stresses in struts.

2. STRESSES DUE TO THE X AND Y COMPONENTS.

The stresses in the struts and stays due to X, Y components of the applied load on the pontoon are in general solved by a method similar to 1.

Example 8.—An airplane weighing 3,000 pounds with wheels 2 feet in diameter and 6 feet apart rests with one wheel 10 inches lower than the other. Find the added bending moment on the axle, assuming each wheel to carry one-half the entire weight.

By section: 23

Given $W = 3{,}000$ lbs. $\alpha = 7°54'$ $R = 12$ ins.

By formula:

$$M = 1/2\ W\ R\ \text{Sin}\ \alpha$$
$$= 1/2\ (3000)\ 12\ (0.1388)$$
$$= 208 \text{ ft. lbs.} \quad \text{Ans.}$$

Example 9.—Find the stresses in the struts, stays, and longerons of the rear segment of the fuselage due to a uniform pressure of 20 pounds per square foot upon the horizontal tail pieces; also those due to gravitational loads alone.

[1] In case the Z component is not in a vertical plane through the pin connections, an equivalent force and couple must be considered.

I. STRESSES DUE TO AIR FORCE ONLY.

1. GENERAL DATA.

$n_1=3.00$; $m_1=0$; $b=19.00$; $p=12.00$; $p_1=22.48$; $p_2=19.24$; $p_3=b$
$n_2=3.00$; $m_2=0$; $c=20.50$; $q=15.00$; $q_1=25.40$; $q_2=20.72$; $q_3=c$
$n_3=3.50$; $m_3=0$; $d=24.00$; $r=18.00$; $r_1=30.00$; $r_2=24.26$; $r_3=d$
$n_4=3.87$; $m_4=0$; $e=26.00$; $s=21.50$; $s_1=33.74$; $s_2=26.29$; $s_3=e$
$n_5=3.75$; $m_5=0$; $f=29.00$; $t=25.37$; $t_1=38.53$; $t_2=29.24$; $t_3=f$
$n_6=3.19$; $m_6=0$; $g=30.87$; $u=29.12$; $u_1=42.44$; $u_2=31.08$; $u_3=g$
$v=32.32$;

$G=507$ on each truss. (See example 2 part II.)

2. ANALYTICAL SOLUTION.

By formulas of figure 32:

UPPER LONGERON STRESSES.

$P'''=O$ 0.00

The formulas of figure 32 apply to all cases and may be reduced to simple forms, for cases of parallel or horizontal longerons, by cancellation. Always rewrite the formulas before solving.

$Q'''=Gb/q$
$=507(19)/15$ ..... [1] 642.19

$R'''=G(b+c)/r$
$=507(19+20.5)/18$ 1,112.58

$S'''=G(b+c+d)/s$
$=507(19+20.5+24)/21.50$ 1,497.41

$T'''=G(b+c+d+e)/t$
$=507(19+20.5+24+26)/25.37$ 1,788.15

$U'''=G(b+c+d+e+f)/u$
$=507(19+20.5+24+26+29)/29.12$ 2,062.80

$V'''=G(b+c+d+e+f+g)/v$
$=507(19+20.5+24+26+29+30.87)/32.32$ 2,343.40

LOWER LONGERON STRESSES.

$P''=p_2Q'''/b$
$=19.24(642.19)/19$ 650.30

$Q''=q_2R'''/c$
$=20.72(1,112.58)/20.5$ 1,124.52

$R''=r_2S'''/d$
$=24.26(1,497.41)/24$ 1,513.63

$S''=s_2T'''/e$
$=26.29(1,788.15)/26$ 1,808.10

$T''=t_2U'''/f$
$=29.24(2,062.80)/29$ 2,079.88

$U''=u_2V'''/g$
$=31.08(2,343.40)/30.87$ 2,358.96

STAY STRESSES.

$P'=p_1[G-P''n_1/p_2]/(q-n_1)$
$=22.48[507-650.30(3)/19.24]/(15-3)$ 759.84

$Q'=q_1[G-Q''n_2/q_2]/(r-n_2)$
$=25.40[507-1,124.52(3)/20.72]/(18-3)$ 582.82

$R'=r_1[G-R''n_3/r_2]/s(-n_3)$
$=30[507-1,513.63(3.5)/24.26]/(21.50-3.5)$ 481.05

[1] Solved two decimal places for comparing methods of solution. Use slide rule for engineering results.

$S' = s_1[G - S''n_4/s_2]/(t - n_4)$
$= 33.74[507 - 1{,}808.10(3.87)/26.29]/(25.375 - 3.87)$ 377.41
$T' = t_1[G - T''n_5/t_2]/(u - n_5)$
$= 38.53[507 - 2{,}079.88(3.75)/29.24]/(29.12 - 3.75)$ 364.67
$U' = u_1[G - U''n_6/u_2]/(v - n_6)$
$= 42.44[507 - 2{,}358.96(3.81)/31.08]/(32.32 - 3.18)$ 386.80

STRUT STRESSES.

$P = G$
$= 507$ 507.00
$Q = P'(q - n_1)/p_1$
$= 759.84(15 - 3)/22.48$ 405.60
$R = Q'(r - n_2)/q_1$
$= 582.82(18 - 3)/25.40$ 344.18
$S = R'(s - n_2)/q_1$
$= 481.05(21.50 - 3.5)/30$ 288.63
$T = S'(t - n_4)/s_1$
$= 377.41(25.375 - 3.875)/33.74$ 240.49
$U = T'(u - n_5)/t_1$
$= 36.467(29.12 - 3.75)/38.53$ 240.16
$V = U'(v - n_6)/u_1$
$= 386.80(32.32 - 3.18)/42.44$ 265.43

3. GRAPHICAL SOLUTION.

The graphical solution is given in figure 35 II.

II. STRESSES DUE TO GRAVITATIONAL LOADS ONLY.

1. GENERAL DATA.

$n_1 = 3.00$;	$b = 19.00$;	$p = 12.00$;	$p_1 = 22.48$;	$p_2 = 19.24$;	$p_3 = b$
$n_2 = 3.00$;	$c = 20.50$;	$q = 15.00$;	$q_1 = 25.40$;	$q_2 = 20.72$;	$q_3 = c$
$n_3 = 3.50$;	$d = 24.00$;	$r = 18.00$;	$r_1 = 30.00$;	$r_2 = 24.26$;	$r_3 = d$
$n_4 = 3.87$;	$e = 26.00$;	$s = 21.50$;	$s_1 = 33.74$;	$s_2 = 26.29$;	$s_3 = e$
$n_5 = 3.75$;	$f = 29.00$;	$t = 25.37$;	$t_1 = 38.53$;	$t_2 = 29.24$;	$t_3 = f$
$n_6 = 3.18$;	$g = 30.87$;	$u = 29.12$;	$u_1 = 42.44$;	$u_2 = 31.08$;	$u_3 = g$
$n_7 = 2.93$;	$h = 41.56$;	$v = 32.31$;	$v_1 = 52.64$;	$v_2 = 41.66$;	$v_3 = h$

$w = 34.75$

$G = 30.00$; $H = 10.00$; $I = 9.00$; $J = 7.50$; $K = 8.00$; $L = 8.50$; $M = 100$

In the case of loads G, H, I, J, K, L, M, etc., on a long truss it is convenient to find their moments about different sections before substituting in the equation.

The use of the table below can be readily seen when substituting in the equations of figure 32.

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Problems in Part III.

Sum of distances.		Moment.
		Distance×G=30
b	19.00	570.00
$b+c$	39.50	1,185.00
$b+c+d$	63.50	1,905.00
$b+c+d+e$	89.50	2,685.00
$b+c+d+e+f$	118.50	3,555.00
$b+c+d+e+f+g$	149.37	4,481.25
$b+c+d+e+f+g+h$	190.93	5,727.90
		Distance×H=10
c	20.50	205.00
$c+d$	44.50	445.00
$c+d+e$	70.50	705.00
$c+d+e+f$	99.50	995.00
$c+d+e+f+g$	130.37	1,303.75
$c+d+e+f+g+h$	171.93	1,719.35
		Distance×I=9
d	24.00	216.00
$d+e$	50.00	450.00
$d+e+f$	79.00	711.00
$d+e+f+g$	109.87	988.87
$d+e+f+g+h$	151.43	1,362.87
		Distance×J=7.5
e	26.00	195.00
$e+f$	55.00	412.50
$e+f+g$	85.87	644.06
$e+f+g+h$	127.43	955.72
		Distance×K=8
f	29.00	232.00
$f+g$	59.87	479.00
$f+g+h$	101.42	811.36
		Distance×L=8.50
g	30.87	262.43
$g+h$	72.43	615.65
		Distance×M=100
h	41.56	4,156.00

2. ANALYTICAL SOLUTION.

UPPER LONGERON STRESSES.

$P''' = O$ 0.00

$Q''' = Gb/q$

$= 570$ [1]$/15$ 38.00

$R''' = [G(b+c) + H(c)]/r$

$= [1{,}185 + 205]/18$ 77.22

$S''' = [G(b+c+d) + H(c+d) + Id]/s$

$= [1{,}905 + 445 + 216]/21.50$ 119.34

$T''' = [G(b+c+d+e) + H(c+d+e) + I(d+e) + Je]/t$

$= 2{,}685 + 705 + 450 + 195]/25.37$ 159.00

$U''' = [G(b+c+d+e+f) + H(c+d+e+f+) + \text{etc.}]/u$

$= [3.555 + 995 + 711 + 412.50 + 232]/29.12$ 202.75

$V''' = [G(b+c+d+e+f+g) + H(c+d+e+f+g+) + \text{etc.}]/v$

$= [4{,}481.25 + 1{,}303.75 + 988.87 + 644.06 + 479 + 262.43]/32.31$ 252.51

$W''' = [G(b+c+d+e+f+g+h) + \text{etc.}]/w$

$= [5{,}727.90 + 1{,}719.35 + 1{,}362.87 + 955.72 + 84.36 + 615.65, \ +4{,}156.00]/34.75$ 409.00

LOWER LONGERON STRESSES.

$P'' = p_2 Q'''/b$

$= 19.24(38)/19$ 38.48

$Q'' = q_2 R'''/c$

$= 20.72(77.22)/20.5$ 78.04

$R'' = r_2 S'''/d$

$= 24.26(119.34)/34$ 120.63

$S'' = s_2 T'''/e$

$= 26.29(159.00)/26$ 160.00

[1] See data table above.

$T''=t_2 U'''/f.$
$=29.24\ (202.75)/29$ 204.42
$U''=u_2 V'''/g.$
$=31.08\ (252.51)/30.875$ 254.18

STAY STRESSES.

$P'=p_1\ [G-P''n_1/p_2]/(q-n_1).$
$=22.48\ [30-38.48(3)/19.24]/(15-3)$ 44.96
$Q'=q_1\ [G+H-Q''n_2/q_2]/(r-n_2).$
$=25.40\ [40-78.04(3)/20.72]/(18-3)$ 48.61
$R'=r_1\ [G+H+I-R''n_3/r_2]/(s-n_3).$
$=30\ [49-120.63(3.5)/24.26]/(21.50-3.5)$ 52.66
$S'=s_1\ [G+H+I+J-S''n_4/s_2]/(t-n_4).$
$=33.74\ [56.50-160.00(3.87)/26.29]/(25.37-3.87)$ 51.66
$T'=t_1\ [G+H+I+J+K-T''n_5/t_2]/(u-n_5).$
$=38.53\ [64.50-204.42(3.75)/29.24]/(29.12-3.75)$ 58.14
$U'=u_1\ [G+H+I+J+K+L-U''n_6u_2]/(v-n_6).$
$=42.44\ [73-254.18(3.18)/31.8]/(32.31-3.18)$ 69.33

STRUT STRESSES.

$P=\mathrm{G}.$
$=30$ 30.00
$Q=H+P'\ (q-n_1)/p_1.$
$=10+44.96(15-3)/22.48$ 34.00
$R=I+Q'(r-n_2)/q_1.$
$=9+48.61(18-3)/25.40$ 37.71
$S=J+R'\ (s-n_3)r_1.$
$=7.50+(52.66)\ (21.50-3.5)/30$ 39.09
$T=K+S'\ (t-n_4)/s_1.$
$=8.00+5166(25.37-3.87)/33.74$ 40.91
$U=L+T'\ (u-n_5)/t_1.$
$=8.50+50.65(29.12-3.75)/38.53$ 41.85

III. GRAPHICAL SOLUTION.

The graphical solution is shown in figure 35.

IV. REFERENCE TABLE FOR STRESSES IN LONGERONS.

Symbol.	Longeron stresses.			
	Upper.	Lower.	Stay stresses.	Strut stresses.
P	0 0	38 5	45.0	30 0
Q	38 0	78 0	48 6	34 0
R	77.2	120.6	52.7	37.7
S	119.3	160 0	51.7	39.1
T	159.0	204.4	.....	40.9
U	202.8	254.2	.....	41.9
V	252.5	.....	.....	.....
W	.....	.....	.....	.....

Example 10.—Find the stresses in the struts, stays, and longerons of the vertical trussing of the front segment of the fuselage shown in figure 35, due to gravitational loads.

I. GENERAL DATA.

$b=19.00;\ m_1=6.12;\ n_1=7.50;\ p=10;\ p_1=24.92;\ p_2=20.43;\ p_3=19.96;$
$c=19.50;\ m_2=1.87;\ n_2=5.50;\ q=23.62;\ q_1=32.10;\ q_2=20.26;\ q_3=19.59;$
$d=13.66;\ r=30.94;\ r_3=13.67;$
$G=165;\ H=11.$

II. ANALYTICAL SOLUTION.

Solution similar to that in example 9.

III. RESULTS.

Symbol.	Longeron stresses.			
	Upper.	Lower.	Stay stresses.	Strut stresses.
P	0.0	142.5	174.2	165.0
Q	133.3	220.5	130.5	103.9
R	212.4			

Example 11.—From the data in the problems above find the stresses and factors of safety for the principal members of the fuselage for a steady circular flight around a level curve of 200 feet radius at 80 miles per hour.

The stresses in the front and rear sections of the fuselage may be found from the gravity stresses for steady level flight in figure 36 by multiplying by a simple ratio. For a velocity of 80 miles per hour and 200 feet radius, formula —, the resultant loading is 2.133 times the gravity loading.

The table below refers to figure 35, and gives the resultant stresses and factors of safety.

Symbol.	Standard strength, pounds.	Stress for steady flight.	Stress for 80M/HR 200 feet RAD.	Factor of safety.
Ba	15,000	0.00		
Cc	15,000	− 71	−151	99
De	15,000	−114	−243	61
Eg	15,000			
Fi	15,000	−147	−314	47
Ge	13,000	−165	−352	37
Hn	13,000	−140	−298	43
Ip	13,000	−115	−245	53
Jn	13,000	− 82	−174	74
Kt	13,000	− 45	− 96	135
Lv	13,000	0.00		
	Strength, pounds.			
Ab	10,500	144	307	34
Ad	10,600	222	473	22
Af	10,700	354	754	14
Oh	9,600			
Ni	8,100	442	942	8.5
Nk	4,800	254	541	8.8
Nm	4,300	204	435	9.8
No	4,300	160	341	12.7
Nq	3,800	121	258	14.7
Ns	3,500	78	166	21
Nu	3,500	39	83	42
Aa				
bc	6,000	112	239	25
de	12,900	302	646	20
fg	10,500			
hi	10,200			
jk	5,600	149	317	17.6
lm	4,500	49	104	43
no	4,600	41	87	53
pq	3,800	39	83	45
rs	3,800	38	81	47
tn	3,800	34	72	52
vm				
ab	4,200	−175	−373	11.2
cd	4,200	−131	−279	15
ef	4,200	−328	−699	6
gh	4,200			
ij	2,100	−236	−503	4.1
kl	2,000	− 69	−147	13.6
mn	2,000	− 59	−125	16
op	2,000	− 53	−113	17
qr	2,000	− 52	−111	18
st	2,000	− 49	−104	19.2
uv	2,000	− 45	− 96	20.8

Example 12.—Find the stresses in the rear segment of the fuselage due to the torsional loads of example 3.

1. GENERAL DATA.

Table for applied torques as found in example 3.

Station.	1	2	3	4	5	6	7
Torque	7,268	7,742	8,216	8,753	9,354	9,954	10,459

Table for length of panels, struts, and stays.

Length of panels.		Length of struts.			Length of stays.		
Station.	Length.	Station.	Upper.	Side.	Station.	Upper.	Side.
1 to 2	19	1	0.00	12	1 to 2		22.48
2 to 3	20.5	2	7.75	15	2 to 3	23.4	25.40
3 to 4	24	3	14.25	18	3 to 4	29.2	30.00
4 to 5	26	4	18.50	21.50	4 to 5	32.9	33.70
5 to 6	29	5	21.37	25.37	5 to 6	36.7	38.50
6 to 7	30.87	6	23.00	29.12	6 to 7	39.0	42.40
7 to 8	41.60	7	24.00	32.3	7 to 8		

Table for lengths of struts and stays in the transverse trussing at the different stations.

Station.	Upper strut.[1]	Side strut.	Diagonal.
2	7.75	15.00	8.44
3	14.25	18.00	11.45
4	18.50	21.50	14.18
5	21.37	25.37	16.58
6	23.00	29.12	18.55
7	24.00	32.30	21.11

[1] See fig. 34.

Computation tables for direction cosine.

Symbol.	Left side stays.						
	l	X	Y	Z	Direction cosines.		
					s_x[1]	s_y[1]	s_z[1]
S_2	27.4[2]	20.5	3.10	18	−0.748	−0.113	−0.657
S_3	32.3	24	2.4	21.5	− .743	− .074	− .666
S_4	36.3	26	1.4	25.4	− .716	− .038	− .699
S_5	41.1	29	1.0	29.1	− .706	− .024	− .708
S_6	44.7	30.9	.6	32.3	− .691	− .013	− .723
S_7	50.1	41.6	0	34.8	− .831	−0.000	− .695

Symbol.	Upper stays.						
	l	X	Y	Z	Direction cosines.		
					t_x	t_y	t_z
T_2	23.4[2]	20.5	10.9	0	−0.884	−0.470	0
T_3	29.0	24	16.7	0	− .828	− .576	0
T_4	32.7	26	19.9	0	− .795	− .608	0
T_5	36.6	29	22.4	0	− .792	− .612	0
T_6	38.8	30.9	23.6	0	− .796	− .608	0
T_7	48.0	41.6	24.0	0	− .867	− .500	0

[1] The direction cosines are found from the projections along X, Y, Z and the true lengths of the struts, stays, etc. The signs are given from observation in fig. 34.
[2] Inches.

Computation tables for direction cosine—Continued.

Symbol.	Right side stays.						
	l	X	Y	Z	Direction cosines.		
					u_x	u_y	u_z
U_2	25.5	20.5	3.10	15	−0.804	+0.121	+0.588
U_3	29.9	24	2.40	18	− .802	+ .080	+ .602
U_4	33.7	26	1.4	21.5	− .771	+ .041	+ .638
U_5	38.6	29	1.0	25.4	− .751	+ .026	+ .658
U_6	42.5	30.9	.6	29.1	− .728	+ .014	+ .685
U_7	52.6	41.6	0	32.3	− .791	+0	+ .614

Symbol.	Lower stays.						
	l	X	Y	Z	Direction cosines.		
					v_x	v_y	v_z
V_2	23.3	20.5	10.9	3.0	−0.880	+0.468	−0.129
V_3	29.1	24.0	16.7	3.4	− .825	+ .574	− .117
V_4	32.8	26.0	19.9	3.9	− .792	+ .607	− .118
V_5	36.7	29.0	22.4	3.7	− .790	+ .612	− .101
V_6	38.9	30.9	23.6	3.2	− .794	+ .606	− .082
V_7	43.9	41.6	24.0	2.3	− .948	+ .546	− .052

Symbol.	Upper longerons, left.						
	l	X	Y	Z	Direction cosines.		
					s_x'	s_y'	s_z'
S_2'	20.8	20.5	3.10	0	+0.986	+0.149	0
S_3'	24.1	24	2.4	0	+ .997	+ .099	0
S_4'	26.1	26	1.4	0	+ .998	+ .053	0
S_5'	29.1	29	1.0	0	+ .999	+ .034	0
S_6'	30.9	30.9	.6	0	+1.000	+ .019	0
S_7'	41.6	41.6	0	0	+1.000	+0	0

Symbol	Upper longerons, right.						
	l	X	Y	Z	Direction cosines.		
					t_x'	t_y'	t_z'
T_2'	20.8	20.5	3.10	0	+0.986	−0.149	0
T_3'	24.1	24	2.4	0	+ .997	− .099	0
T_4'	26.0	26	1.4	0	+ .998	− .053	0
T_5'	29.1	29	1.0	0	+ .999	− .034	0
T_6'	30.9	30.9	.6	0	+1.000	− .019	0
T_7'	41.6	41.6	0	0	+1.000	0	0

Symbol.	Lower longerons, left.						
	l	X	Y	Z	Direction cosines.		
					u_x'	u_y'	u_z'
U_2'	20.9	20.5	3.10	3.0	+0.981	−0.149	+0.143
U_3'	24.2	24	2.4	3.4	+ .992	− .099	+ .140
U_4'	26.1	26	1.4	3.8	+ .994	− .053	+ .146
U_5'	29.2	29	1.0	3.7	+ .999	− .034	+ .126
U_6'	30.9	30.9	.6	3.2	+1.00	− .019	+ .103
U_7'	41.6	41.6	0	2.0	+1.00	0.000	+ .048

Computation tables for direction cosine—Continued.

Symbol.	Lower longerons, right.						
	l	X	Y	Z	Direction cosines.		
					v_x'	v_y'	v_z'
V_2'	20.9	20.5	3.10	3.0	−0.981	−0.149	−0.143
V_3'	24.2	24	2.40	3.4	− .992	− .099	− .140
V_4'	26.1	26	1.4	3.9	− .994	− .053	− .149
V_5'	29.2	29	1.0	3.7	− .999	− .034	− .126
V_6'	30.9	30.9	.6	3.2	−1.00	− .019	− .103
V_7'	41.6	41.6	0	2.0	−1.00	0.000	− .048

II. SOLUTION.

FOR TORQUE OF 7,742 INCHES-POUNDS AT STATION NO. 2.

Given torque = 7,742 ins.-lbs.; $l = 8.44$ ins.; $b = 15$ ins.; $a = 7.74$ ins.

Then by figure 34:

$R = \text{torque}/4l$
$= 7{,}742/4\ (8.44)$ ..... 229.32 lbs.

$P = R\ b/2l$
$= 229.32(15)/2(8.44)$ 203.77

$Q = Ra/2l$
$= 229.32\ (7.75)/2(8.44)$ 105.28

Substituting these values in formulas of figure 34:

$s_yS + s_y'S' + t_yT + t_y'T' + 2\ P = 0 \quad -0.113S + 0.149S' - 0.470T - 0.149\,T' + 2(203.77) = 0$ (1)

$t_zT + t_z'\,T' + u_zU + u'^1\,U_2 - 2Q = 0 \quad +0 + 0.588\ U + 0.143\,U' - 2(105.28) = 0$ (2)

$u_yU + u_y'\,U' + v_y\,V + v_y'\,V' - 2P = 0 \quad +0.121\,U - 0.149\,U' + 0.468\,V + 0.149\,V' - 2(203.77) = 0$ (3)

$v_zV + v_z'\,V + s_zS + s_z'S' + 2\ Q = 0 \quad -0.129\,V + 0.143\,V' - 0.657S + 0 + 2(105.28) = 0$ (4)

$S + s'\ S^1 = 0 \quad -0.748S + 0.986S' = 0;\ S' = 0.759S$ (5)

$t_xT + t_x'\,T' = 0 \quad -0.884\,T + 0.986\,T' = 0;\ T' = 0.897T$ (6)

$u_xU + u_x'\,U' = 0 \quad -0.804\,U + 0.981U' = 0;\ U' = 0.819U$ (7)

$v_xV + v_x'\,V' = 0 \quad -0.880\,V + 0.981V' = 0;\ V' = 0.897V$ (8)

Substituting values of S', T', U', V' from equations 5, 6, 7, 8, in equations 1, 2, 3, 4 we find—

$S = 320.7.$
$T = 675.0.$
$U = 298.7.$
$V = 678.0.$

Again by equations 5, 6, 7, 8—

$S' = 243.6.$
$T' = 605.5.$
$U' = 243.9.$
$V' = 608.2.$

In a similar manner the stresses may be determined for stations 3, 4, etc. The table below gives these results for the given torsion loads.

Stations.	S	T	U	V	S'	T'	U'	V'
2	320.7	675.0	298.7	678.0	243.6	605.5	243.9	608.2
3	334.4	426.1	311.5	427.5	249.2	354.0	251.8	355.8
4	288.0	360.0	268.1	360	206.8	286.9	208.1	286.9
5	256.0	337.0	240.7	337	181.0	267.2	181.2	266.6
6	230.0	338.0	218.8	339	148.9	269.0	159.3	269.1
7	223.1	417.3	238.2	382	185.4	361.8	188.4	362.1

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PART V.

ILLUSTRATIONS FOR PARTS I, II, III, IV.

By A. F. Zahm and L. H. Crook.

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FIG. 1.—Contour maps of pressure on top and bottom surfaces of typical aerofoil (model R. A. F. 6, aspect ratio 6 to 1, air at standard density).

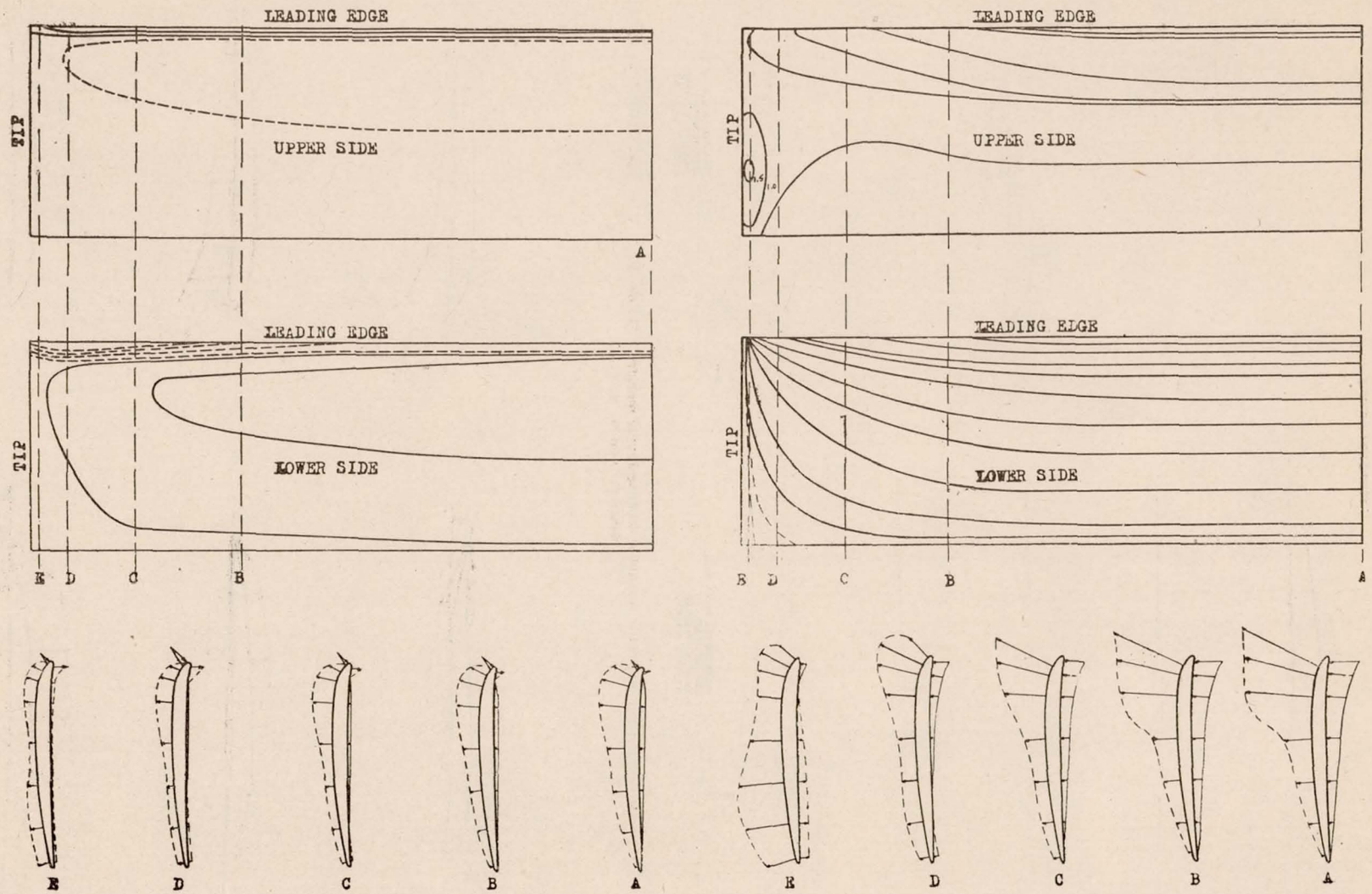


FIG. 2.—Pressure distribution on median section of R. A. F. 6 aerofoil of 1 to 6 aspect ratio at 30 feet per second, air at standard density.

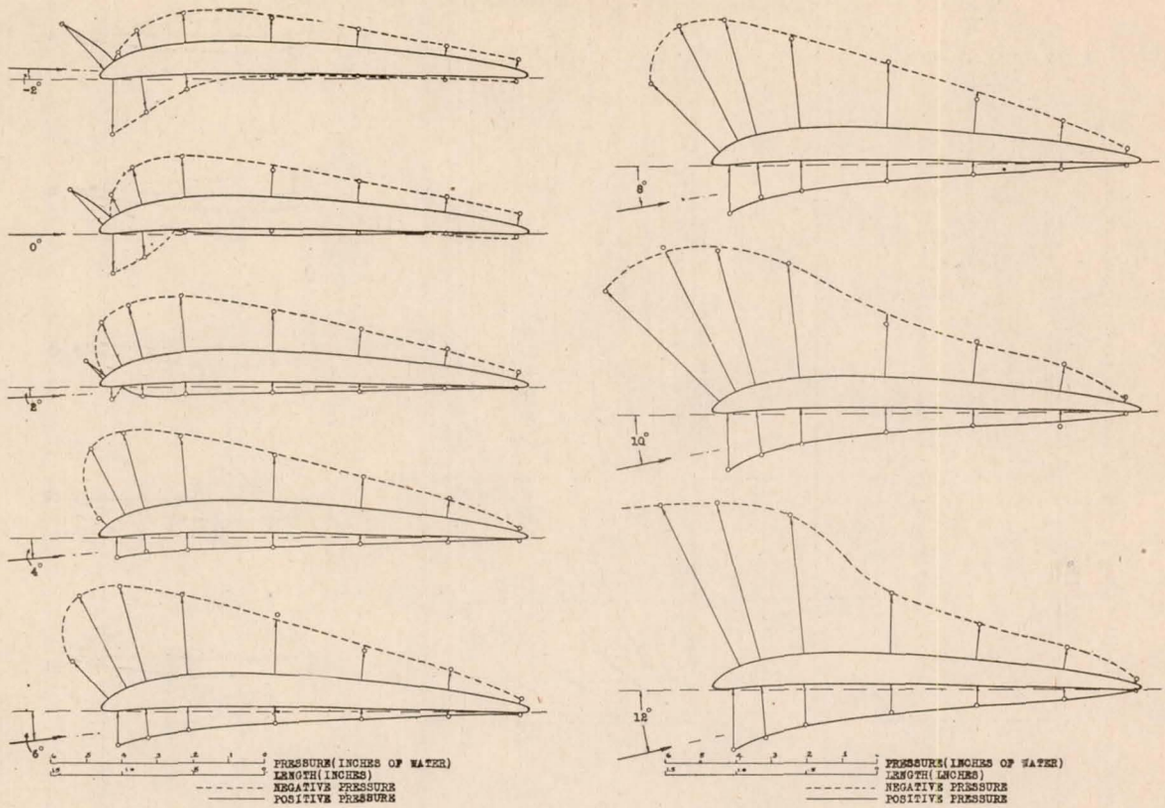


FIG. 3.—Pressure distribution on typical aerofoil with hinged rear margin. (Model R. A. F. 6, aspect ratio 1 to 6, standard air density, speed 40 m. p. h.)

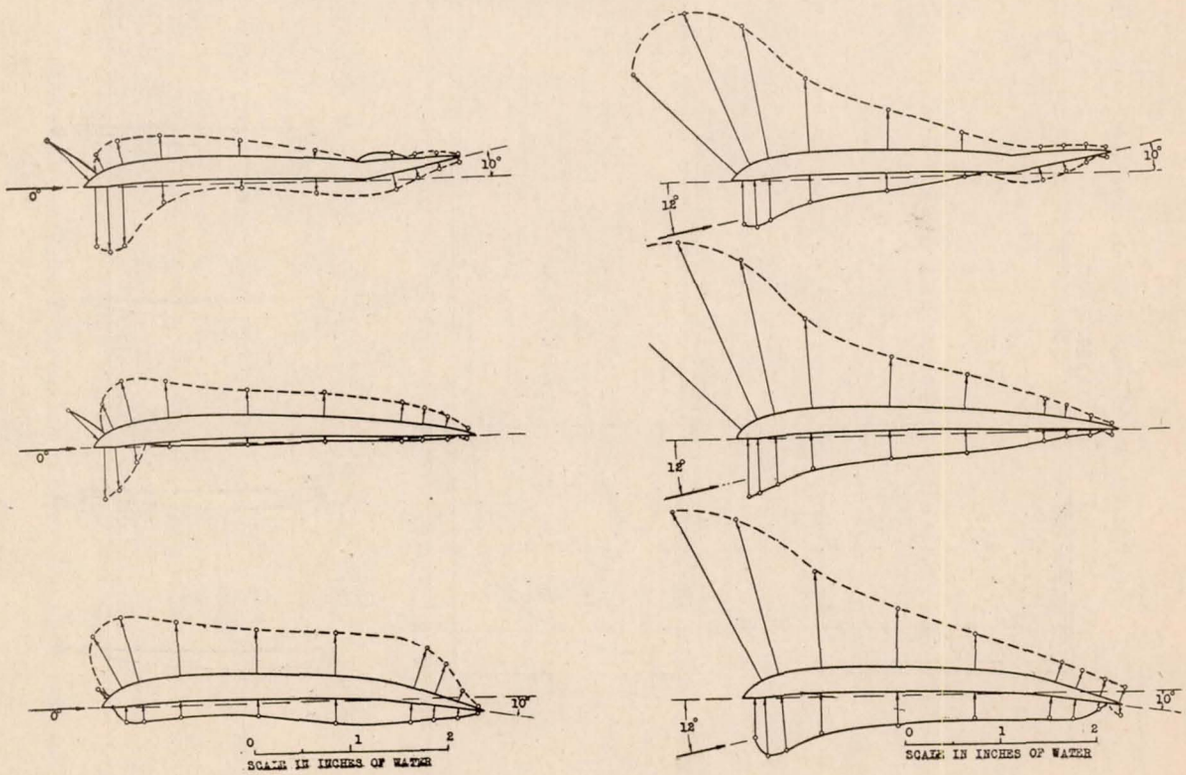
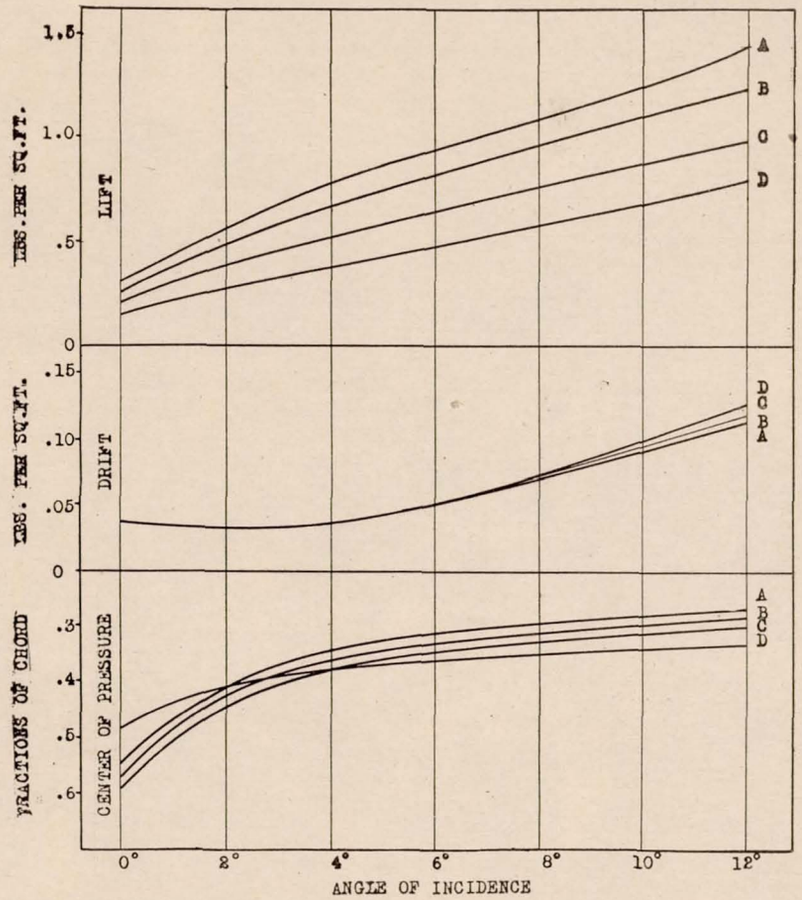


FIG. 4.—Lift, drag, and center of pressure for typical aerfoil at various cross sections and angles of incidence. (R. A. F. 6, 6 to 1 aspect ratio, 30 feet per second air speed.)



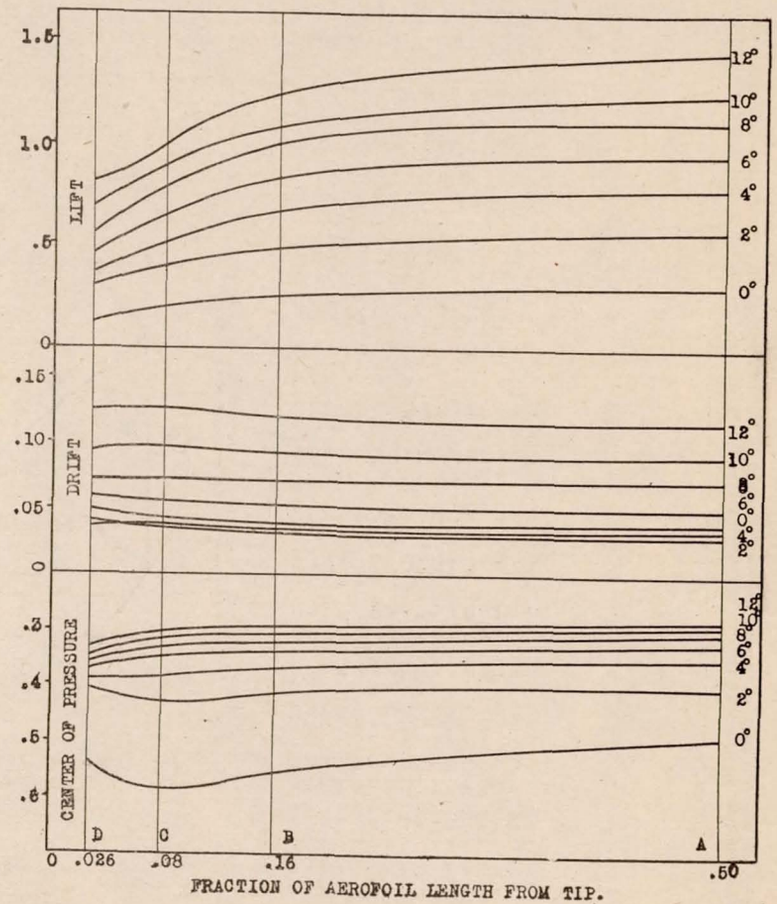
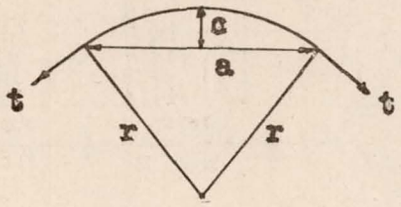


FIG. 5.—Values of the natural angle of bank α degrees, centrifugal force F, and whole force P perpendicular to the wings, for an airplane in steady circular flight around a level curve of radius R feet. F and P expressed as a fraction of the whole weight W.

Flight speed.	R=100 feet.			R=200 feet.			R=300 feet.			R=400 feet.			R=500 feet.			R=600 feet.			R=800 feet.		
Miles per hour.	α	F	P	α	F	P	α	F	P	α	F	P	α	F	P	α	F	P	α	F	P
	° ′			° ′			° ′			° ′			° ′			° ′			° ′		
20	14 56	0.267	1.035	7 30	0.133	1.009	5 5	0.089	1.004	3 49	0.067	1.002	3 9	0.053	1.002	2 33	0.044	1.001	1 55	0.033	1.001
30	30 58	.600	1.166	16 42	.300	1.044	11 19	.200	1.020	8 32	.150	1.011	6 51	.120	1.007	5 43	.100	1.005	4 18	.075	1.003
40	46 51	1.067	1.462	28 4	.533	1.133	19 34	.356	1.061	14 56	.267	1.035	12 3	.213	1.022	10 5	.178	1.016	7 36	.133	1.009
50	59 2	1.667	1.944	39 48	.833	1.302	29 3	.556	1.144	22 37	.417	1.083	18 26	.333	1.054	15 31	.278	1.038	11 46	.208	1.021
60	67 23	2.400	2.600	50 12	1.200	1.562	38 40	.800	1.281	30 58	.600	1.166	25 38	.480	1.109	21 48	.400	1.077	16 42	.300	1.044
70	72 59	3.267	3.416	58 31	1.633	1.915	47 26	1.089	1.478	39 14	.817	1.291	33 9	.653	1.195	28 34	.544	1.139	22 13	.408	1.080
80	76 49	4.267	4.383	64 53	2.133	2.356	54 53	1.422	1.739	46 51	1.067	1.462	40 29	.853	1.315	35 25	.711	1.227	28 4	.533	1.133
90	79 31	5.400	5.492	69 41	2.700	2.879	60 57	1.800	2.059	63 28	1.350	1.680	47 12	1.080	1.472	41 59	.900	1.345	34 1	.675	1.206
100	81 28	6.667	6.741	73 18	3.333	3.480	65 46	2.222	2.437	59 2	1.667	1.944	53 8	1.333	1.667	48 1	1.111	1.495	39 48	.833	1.302
110	82 56	8.067	8.128	76 5	4.033	4.155	69 36	2.689	2.869	63 37	2.017	2.251	58 12	1.613	1.898	53 21	1.344	1.675	45 14	1.008	1.420
120	84 3	9.600	9.652	78 14	4.800	4.903	72 39	3.200	3.353	67 23	2.400	2.600	62 29	1.920	2.165	58 0	1.600	1.887	50 12	1.200	1.562
130	84 56	11.27	11.31	79 56	5.633	5.721	75 5	3.755	3.886	70 27	2.817	2.989	66 4	2.253	2.465	61 58	1.878	2.127	54 37	1.408	1.727
140	85 37	13.07	13.10	81 18	6.533	6.609	77 4	4.356	4.469	72 59	3.267	3.416	69 4	2.613	2.798	65 20	2.178	2.396	58 31	1.633	1.915
150	86 11	15.00	15.03	82 24	7.500	7.566	78 41	5.000	5.099	75 4	3.750	3.881	71 34	3.000	3.162	68 12	2.500	2.693	61 56	1.875	2.135
175	87 12	20.42	20.44	84 24	10.21	10.26	81 38	6.806	6.879	78 55	5.104	5.201	76 14	4.083	4.204	73 37	3.403	3.546	68 36	2.552	2.741
200	87 51	26.67	26.69	85 43	13.33	13.37	83 35	8.889	8.945	81 28	6.667	6.741	79 23	5.333	5.426	77 19	4.444	4.556	73 18	3.33	3.480

FIG. 6.—Tension in airplane fabric in terms of pressure, bulge, and rib spacing.



$t = pa^2/144(8c)$.

Depth of bulge c, inches.	Tension t in pounds per linear inch for various air pressures, p pounds per square foot.							
	p=5.	p=8.	p=10.	p=15.	p=20.	p=25.	p=50.	p=100.
	For rib spacing a=12 inches; t=p/8c.							
0.1	6.25	10.00	12.50	18.75	25.00	31.25	62.50	125.00
.2	3.12	5.00	6.25	9.37	12.50	15.62	31.25	62.50
.3	2.08	3.33	4.16	6.25	8.33	10.41	20.83	41.66
.4	1.56	2.50	3.12	4.68	6.25	7.81	15.62	31.25
.5	1.25	2.00	2.50	3.75	5.00	6.25	12.50	25.00
	For rib spacing a=13 inches; t=.1465 p/c.							
.1	7.32	11.72	14.65	22.00	29.30	36.60	73.25	146.50
.2	3.66	5.86	7.32	11.00	14.65	18.30	36.62	73.25
.3	2.44	3.91	4.88	7.33	9.76	12.20	24.41	48.80
.4	1.82	2.93	3.66	5.50	7.32	9.15	18.31	36.60
.5	1.46	2.34	2.93	4.40	5.86	7.32	14.65	29.30
	For rib spacing a=14 inches; t=.1701 p/c.							
.1	8.50	13.61	17.01	25.51	34.02	42.52	85.05	170.10
.2	4.25	6.80	8.50	12.75	17.01	21.26	42.52	85.00
.3	2.83	4.53	5.67	8.50	11.34	14.17	28.35	56.70
.4	2.12	3.40	4.25	6.37	8.50	10.63	21.26	42.52
.5	1.70	2.72	3.40	5.10	6.80	8.50	17.01	34.00
	For rib spacing a=15 inches; t=.1953 p/c.							
.1	9.76	15.62	19.53	29.29	39.06	48.82	97.65	195.3
.2	4.88	7.81	9.76	14.64	19.53	24.41	48.82	97.6
.3	3.25	5.20	6.51	9.76	13.02	16.27	32.55	65.1
.4	2.44	3.90	4.88	7.32	9.76	12.20	24.41	48.8
.5	1.95	3.12	3.90	5.85	7.81	9.76	19.53	39.0

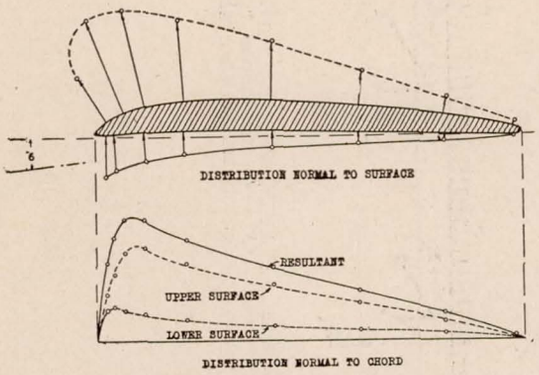


FIG. 7.—Typical pressure distribution on wing plane resolved *normal to chord.*

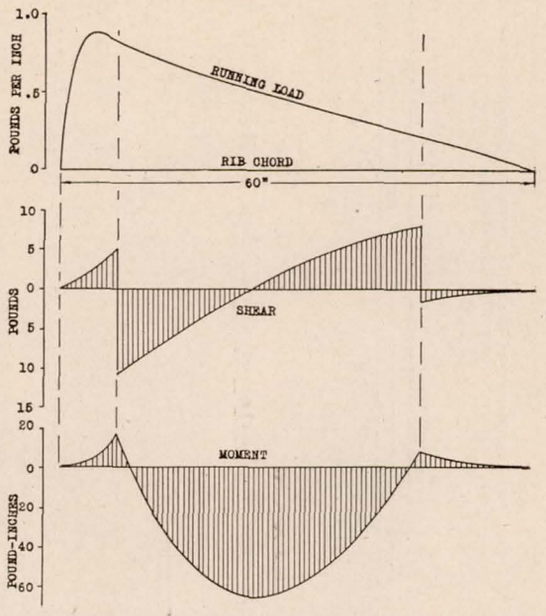


FIG. 8.—Shear and moment on rib of a wing plane due to loading normal to chord.

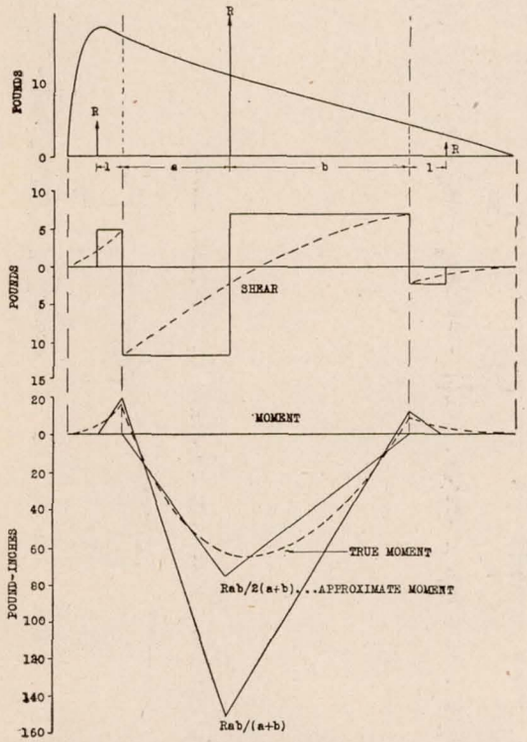


FIG. 9.—Shearing force and bending moment on wing rib due to three concentrated loads approximately representing the loading normal to chord.

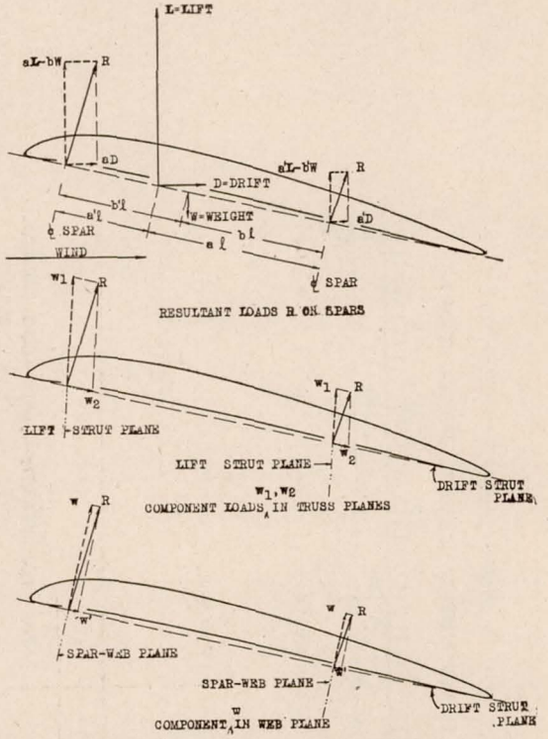
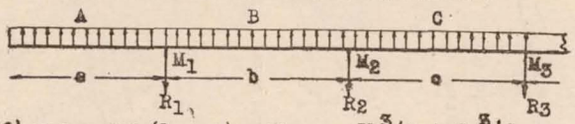


FIG. 10.—Resolution of wing plane loads into wing spar loads (pictured in sequence).

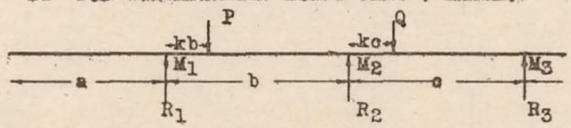
FIG. 11.—Forms of the three-moment theorem.

I FOR RUNNING LOADS ONLY (CLAPEYRON).



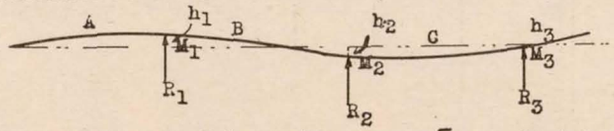
(1) $M_1 b + 2M_2(b + c) + M_3 c = Bb^3/4 + Cc^3/4$

II FOR CONCENTRATED LOADS ONLY (BRESSE).



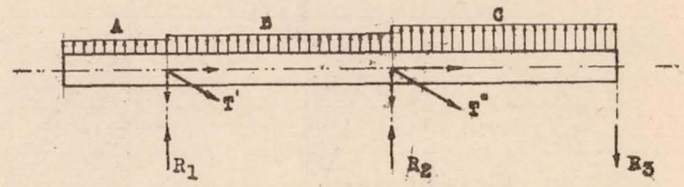
(2) $M_1 b + 2M_2(b + c) + M_3 c = -Pb^2(k_1 - k_1^3) - Qc^2(2k_2 - 3k_2^2 + k_2^3)$

FOR RUNNING LOADS WITH SUPPORTS AT DIFFERENT LEVELS.

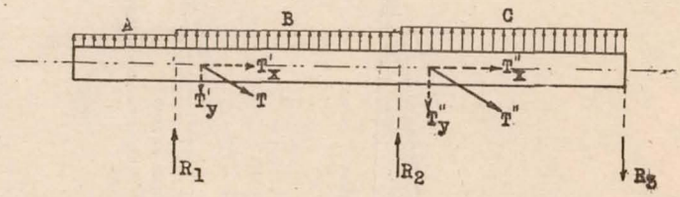


(1) $M_1 b + 2M_2(b + c) + M_3 c = +Bb^3/4 + Cc^3/4 + 6EI\left[(h_2 - h_1)b + (h_2 - h_3)c\right]$

FIG. 12.—Application of the three-moment theorem to cases of eccentric bracing.



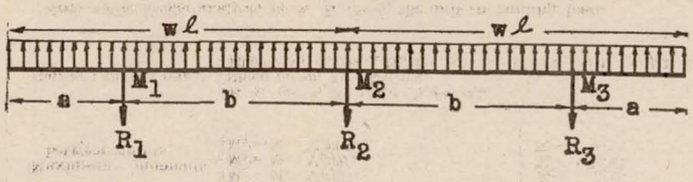
For centrally attached stays, form 1, Fig.11, is applied.



For stay aside the strut axis the tension is replaced by its horizontal and vertical components T_x, T_y, the latter being regarded as a concentrated load and treated by form 2, Fig. 11.

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FIG. 13.—Bending moments and reactions for a continuous beam symmetrically supported.

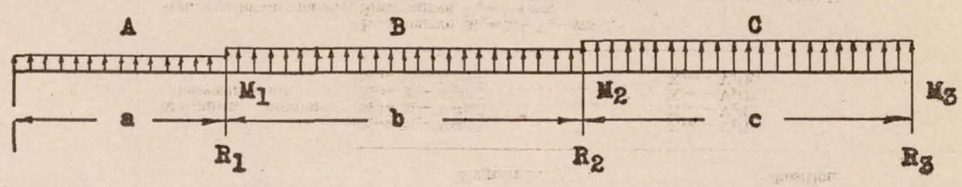


Bending moments.....	$M_1 = wa^2/2 = M_3$. $M_2 = wb^2/8$.		
	Shear left of pin.	Shear right of pin.	Pin reactions.
Joint shears and pin reactions.	$U_1 = wa$..... $U_2 = V_1 + wb$..... $U_3 = V_2 + wb$.....	$V_1 = (M_2 - M_1)/b - wb/2$..... $V_2 = (M_3 - M_2)/b - wb/2$..... $V_3 = (O - M_3)/a - wa/2$.....	$R_1 = w(4l^2 - b^2)/8b$. $R_2 = 2(wl - R_1)$. $R_3 = R_1$.
	Magnitude.		Position.
Maximum moments between joints.	$M_1 = M_1 - V_1^2/2w$..... $M_2 = M_2 - V_2^2/2w$.....		$X_1 = -V_1/w$. $X_2 = -V_2/w$.
Gen. eqs. for any panel	B. M. curve, $M_x = M + Vx + wx^2/2$. Shear curve, $V_x = V + wx$. Elastic curve, $y = -x[12M(l-x) + 4V(l^2 - x^2) + w(l^3 - x^3)]/24$ EI.		

R_1 and R_2 as fractions of wl.

b/l	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3
R_1	.375	.443	.525	.627	.758	.937	1.20	1.638
R_2	1.250	1.114	.950	.746	.484	.126	−.40	−1.276

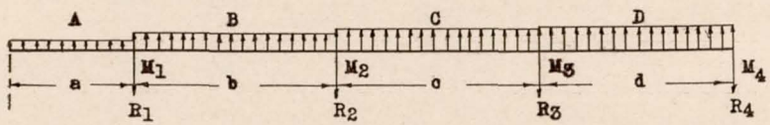
FIG. 14.—Bending moments, shears, and reactions for a continuous beam supported at three points and having one end overhanging. Uniformly loaded on each panel.



Auxiliary symbols.....	$1 = (Bb^3 + Cc^3)/4 - Aa^2b/2$; $h = 2(b+c)$.		
Joint bending moments	$M_1 = Aa^2/2$. $M_2 = 1/h$.		
	Shear left of pin.	Shear right of pin.	Pin reactions.
Joint shears and pin reactions.	$U_1 = aA$..... $U_2 = V_1 + Bb$..... $U_3 = V_2 + Cc$.....	$V_1 = (M_2 - M_1)/b - Bb/2$..... $V_2 = (o - M_2)/c - Cc/2$.....	$R_1 = U_1 - V_1$. $R_2 = U_2 - V_2$. $R_3 = U_3 - o$.
	Magnitude.		Position.
Maximum moments between joints.	$M_1' = M_1 - V_1^2/2B$..... $M_2' = M_2 - V_2^2/2C$.....		$X_1 = -V_1/B$. $X_2 = -V_2/O$.
Gen. eqs. for any panel	B. M. curve, $M_x = M + Vx + wx^2/2$. Shear curve, $V_x = V + wx$. Elastic curve, $y = -x[12M(1-x) + 4V(1^2 - x^2) + w(1^3 - x^3)]/24$ EI.		

NOTE.—For briefer analysis, let A, B, C = w, the uniform running load.

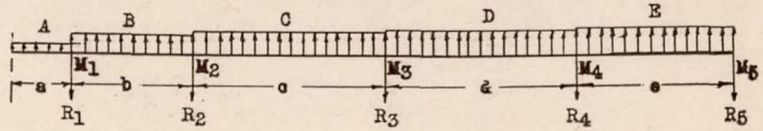
FIG. 15.—Bending moments, shears, and reactions for a continuous beam supported at four points and having one end overhanging. Uniformly loaded on each panel.



Auxiliary symbols	$l=(Bb^3+Cc^3)/4-Aa^2b/2$; $h=2(b+c)$.		
	$m=(Cc^3+Dd^3)/4$; $i=2(c+d)$.		
Joint bending moments	$M_1=Aa^2/2$.		
	$M_2=(li-mc)/(hi-c^2)$.		
	$M_3=(l-M_2h)/c$.		
	Shear left of pin.	Shear right of pin.	Pin reactions.
Joint shears and pin reactions.	$U_1=aA$	$V_1=(M_2-M_1)/b-Bb/2$	$R_1=U_1-V_1$.
	$U_2=V_1+Bb$	$V_2=(M_3-M_2)/c-Cc/2$	$R_2=U_2-V_2$.
	$U_3=V_2+Cc$	$V_3=(o-M_3)/d-Dd/2$	$R_3=U_3-V_3$.
	$U_4=V_3+Dd$		$R_4=U_4-o$.
	Magnitude.		Position.
Maximum moments between points.	$M_1'=M_1-V_1^2/2B$		$X_1=-V_1/B$.
	$M_2'=M_2-V_2^2/2C$		$X_2=-V_2/C$.
	$M_3'=M_3-V_3^2/2D$		$X_3=-V_3/D$.
Gen. eqs. for any panel.	B. M. curve, $M_x=M+Vx+wx^2/2$.		
	Shear curve, $V_x=V+wx$.		
	Elastic curve, $y=x\,[12M(l-x)+4V(l^2-x^2)+w(l^3-x^3)]/24\,EI$.		

NOTE.—For briefer analysis, let A, B, C=v, the uniform running load.

FIG. 16.—Bending moments, shears, and reactions for a continuous beam supported at five points and having one end overhanging. Uniformly loaded on each panel.



Auxiliary symbols	$l=(Bb^3+Cc^3)/4-bAa^2/2$; $h=2(b+c)$.		
	$m=(Cc^3+Dd^3)/4$; $i=2(c+d)$.		
	$n=(Dd^3+Ee^3)/4$; $j=2(d+e)$.		
Joint bending moments	$M_1=Aa^2/2$.		
	$M_2=\{1(ij-d^2)-c(jm-nd)\}/[h(ij-d^2)-c^2j]$.		
	$M_3=(1-hM_2)/c$.		
	$M_4=(n-M_3d)j$.		
	Shear left of pin.	Shear right of pin.	Pin reactions.
Joint shears and pin reactions.	$U_1=Aa$	$V_1=(M_2-M_1)/b-Bb/2$	$R_1=U_1-V_1$.
	$U_2=V_1+Bb$	$V_2=(M_3-M_2)/c-Cc/2$	$R_2=U_2-V_2$.
	$U_3=V_2+Cc$	$V_3=(M_4-M_3)/d-Dd/2$	$R_3=U_3-V_3$.
	$U_4=V_3+Dd$	$V_4=(o-M_4)/e-Ee/2$	$R_4=U_4-V_4$.
	$U_5=V_4+El$		$R_5=U_5-o$.
	Magnitude.		Position.
Maximum moments between joints.	$M_1'=M_1-V_1^2/2B$		$X_1=-V_1/B$.
	$M_2'=M_2-V_2^2/2C$		$X_2=-V_2/C$.
	$M_3'=M_3-V_3^2/2D$		$X_3=-V_3/D$.
	$M_4'=M_4-V_4^2/2E$		$X_4=-V_4/E$.
Gen. eqs. for any panel.	B. M. curve, $M_x=M+V_x+wx^2/2$.		
	Shear curve, $V_x=V+wx$.		
	Elastic curve, $y=-x[12M(1-x)+4V(l^2-x^2)+w(l^3-x^3)]/24\,EI$.		

NOTE.—For briefer analysis, let A, B, C=w, the uniform running load.

FIG. 17.—Shear and moment on upper and lower spars in plane of front struts.

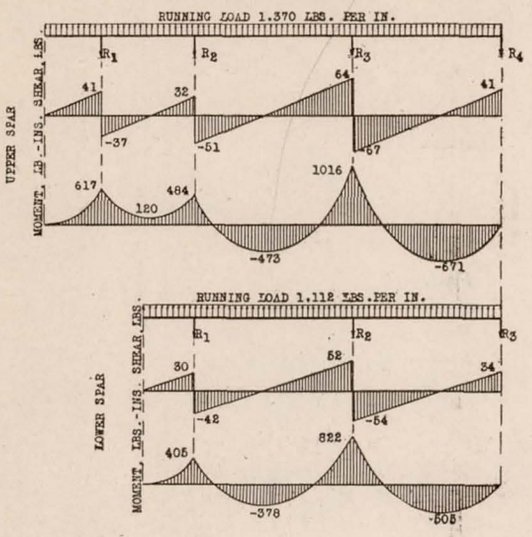


FIG. 18.—Bending moments for a uniformly loaded continuous beam with pin supports and stays attached aside from strut axis.

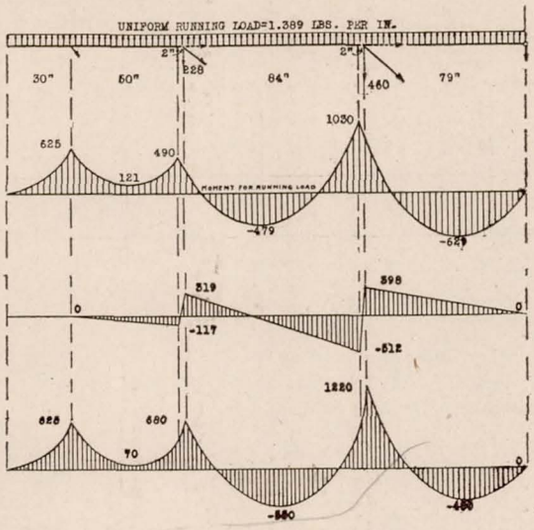


FIG. 19.—Comparison of distances to maximum deflection and maximum bending moment for typical spar panel.

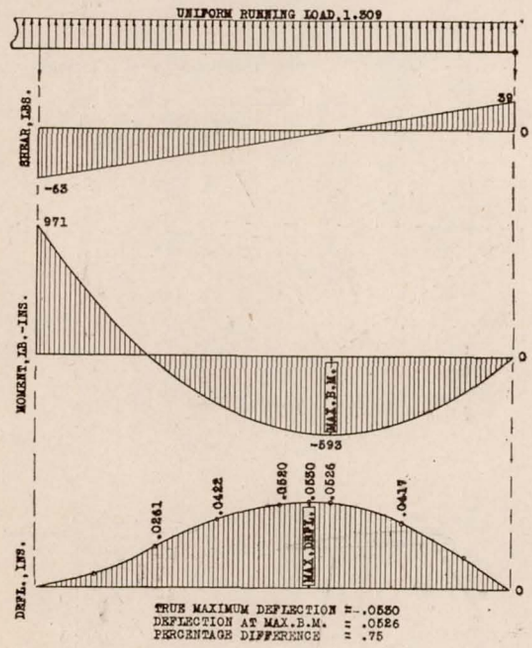
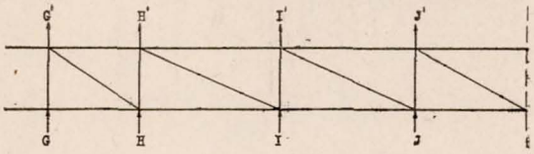


FIG. 20.—Concentrated loads on drag trussing in terms of pin reactions R., and strut and stay resistance.



I. Biplane Trussing.

(*a*) *For upper drag trussing*—

1. Loads due to *front* upper spar plus resistance of front struts and stays.

$$G=r_1+R_1\ N.$$
$$H=r_2+R_2\ N.$$
$$I=r_3+R_3\ N.$$
$$J=r_4+R_4\ N.$$

2. Loads due to *rear* upper spar plus resistance [1] of rear struts and stays.

$$G'=r_1+R_1\ N_1.$$
$$H'=r_2+R_2\ N_1.$$
$$I'=r_3+R_3\ N_1.$$
$$J'=r_4+R_4\ N_1.$$

Where r_1, r_2, r_3, etc., equal one-half the air resistance of the struts and stays adjacent to the pins; $N=w_2/w_1$, the ratio of the running load on front spar in plane of drag trussing to the running load on front spar in plane of lift trussing; $N_1=w_2/w_1$, the ratio of the running load on rear spar, in plane of lift trussing to running load on rear spar in plane of drag trussing;

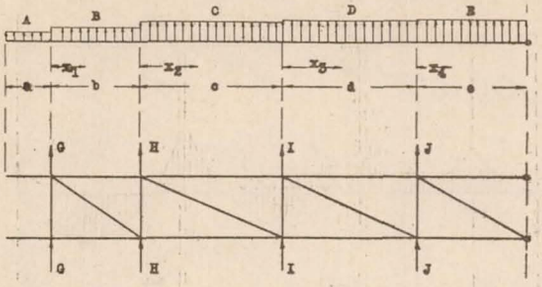
(*b*) *For lower drag trussing.*—For concentrated loads on lower drag trussing change the word *upper* into *lower* in (*a*) above.

II. Any Trussing.

The formulas above apply also to drag trussing in monoplanes or multiplanes.

[1] Consider the resistance as acting only in the plane of drag trussing.

FIG. 21.—Concentrated loads on drag trussing in terms of strut and stay resistance and running loads on spars.



I. Biplane Trussing.

(*a*) *For upper drag trussing.*—

1. Loads due to the *front* upper spar plus one-half the resistance of the *front* struts and stays.

$$G=r_1+Aa+Bx_1$$
$$H=r_2+B(b-x_1)+Cx_2$$
$$I=r_3+C(c-x_2)+Dx_3$$
$$J=r_4+D(d-x_3)+Ex_4$$

2. Loads due to the *rear* upper spar plus one-half the resistance of the *rear* struts and stays.

$$G'=r'_1+Aa+Bx_1$$
$$H'=r'_2+B(b-x_1)+Cx_2$$
$$I'=r'_3+C(c-x_2)+Dx_3$$
$$J'=r'_4+D(d-x_3)+Ex_4$$

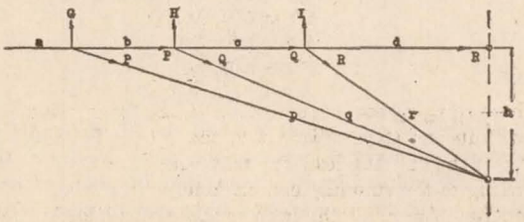
Where r_1, r_2, r_3, etc., are the loads due to one-half the air resistance* of the front struts and stays; r_1', r_2', r_3', etc., are the loads due to one-half the air resistance* of the rear struts and stays; x_1, x_2, etc., the distances to the points of zero shear.

(*b*) *For lower drag trussing.*—Treatment similar to above.

II. Any Trussing.

The formulas above apply also to the drag trussing in monoplanes or multiplanes.

FIG. 23.—Endwise stresses in terms of loads and size in any monoplane wing truss. Analytical treatment.



STAY STRESSES.

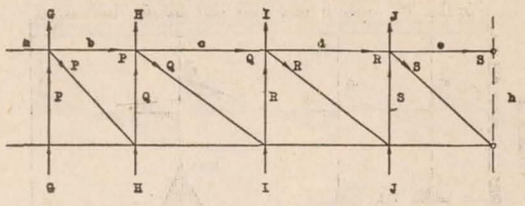
$$P'=pG'/h$$
$$Q'=qH'/h$$
$$R'=rI'/h$$

SPAR STRESSES.

$$P''=(b+c+d)G/h$$
$$Q''=(b+c+d)G/h+(c+d)H/h$$
$$R''=(b+c+d)G/h+(c+d)H/h+dI/h$$

*Consider the resistance as acting only in the plane of the drag trussing.

FIG. 22.—Endwise stresses in a biplane wing truss with parallel spars. Analytical treatment.



STRUT STRESSES.

$$P=G=G$$
$$Q=G+G'+H=P+G'+H$$
$$R=G+G'+H+H'+I=Q+H'+I$$
$$S=G+G'+H+H'+I+I'+J=R+I'+J$$

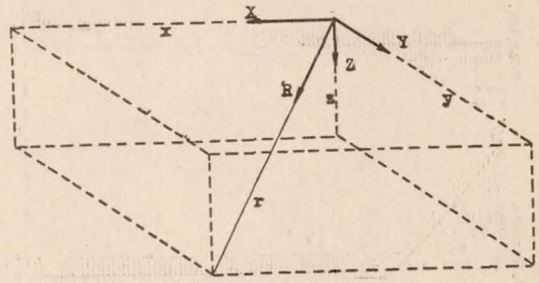
STAY STRESSES.

$$P'=p(G+G')/h=p(P+G')/h=pn_1$$
$$Q'=q(G+G'+H+H')/h=q(Q+H')/h=qn_2$$
$$R'=r(G+G'+H+H'+I+I')/h=r(R+I')/h=rn_3$$
$$S'=s(G+G'+H+H'+I+I'+J+J')/h=s(S+J')/h=sn_4$$

SPAR STRESSES.

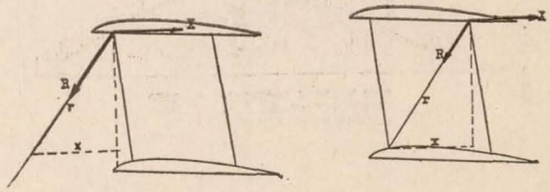
$$P''=(G+G')b/h=b(P+G')/h=bn_1$$
$$Q''=[(G+G')(b+c)+c(H+H')]/h=P''+c(Q+H')/h=P''+cn_2$$
$$R''=[(G+G')(b+c+d)+(c+d)(H+H')+d(I+I')]/h=Q''+d(R+I')/h=Q''+dn_3$$
$$S''=[(G+G')(b+c+d+e)+(c+d+e)(H+H')+\text{etc.}]/h=R''+e(S+J')/h=R''+en_4$$

FIG. 24.—Three-component resolution of stay tension.



I. General Case.

$$R/r=X/x=Y/y=Z/z$$

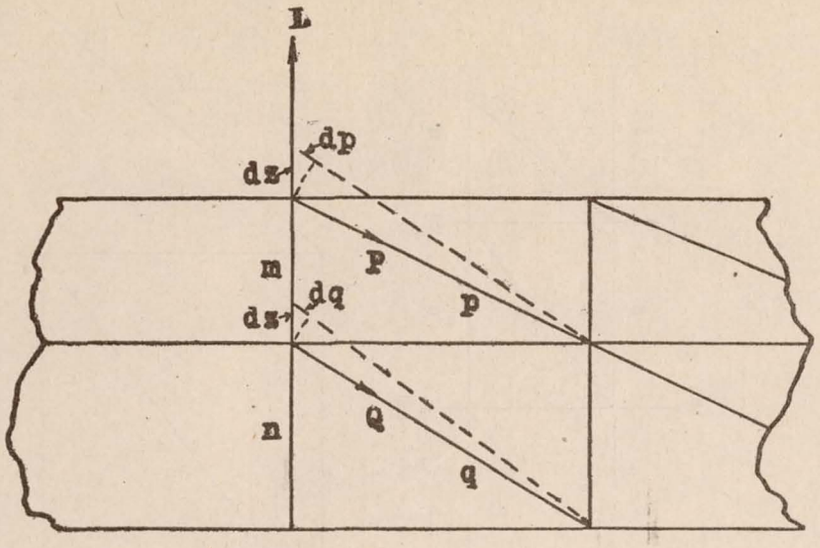


II. Special Cases.

(*a*) For cabane stays,
$R=rX/x$

(*b*) For cross diagonal,
$R=rX/x$

FIG. 25.—Endwise stresses in terms of loads and size in a multiplane wing truss. Analytical treatment.



GENERAL THEORY.

Let L be the total lift on a multiplane strut, as shown,

P, Q, tensions in the stays p, q,

dp, dq, stretches of the lengths p, q, for vertical strain dz of truss,

m, n, strut lengths between joints,

A, B, E, cross sectional areas of stays and modulus of elasticity.

Then $L=Pm/p+Qn/q+$etc., for more planes, if any,

$P=AEdp/p$,

$Q=BEdq/q$,

$R=$etc., for more planes, if any.

$dz=qdq/n=pdp/m=$etc., for more planes, if any.

$P/Q=Amq^2/Bnp^2$, $Q/R=$etc., for more planes, if any.

FOR A TRIPLANE.

$P=LAmq^2/(Am^2q^2/p+Bn^2p^2/q)$.

$Q=LBnp^2/(Am^2q^2/p+Bn^2p^2/q)$.

FOR A QUADRUPLANE.

$P=LAmr^2/(Am^2r^2/p+Bn^2r^2p^2/q^3+C\,o^2p^2/r)$.

$Q=LBnp^2/(Bn^2p^2/q+Co^2p^2q^2/r^3+Am^2q^2/p)$.

$R=LCoq^2/(Co^2q^2/r+Am^2q^2r^2/p^3+Bn^2r^2/q)$.

NOTE.—In a similar way the equation for any multiplane may be written.

Having thus obtained the strut and stay stresses in a multiplane, the spar stresses follow by ordinary statics.

FIG. 26.—Endwise stresses in a monoplane wing truss. Graphical treatment.

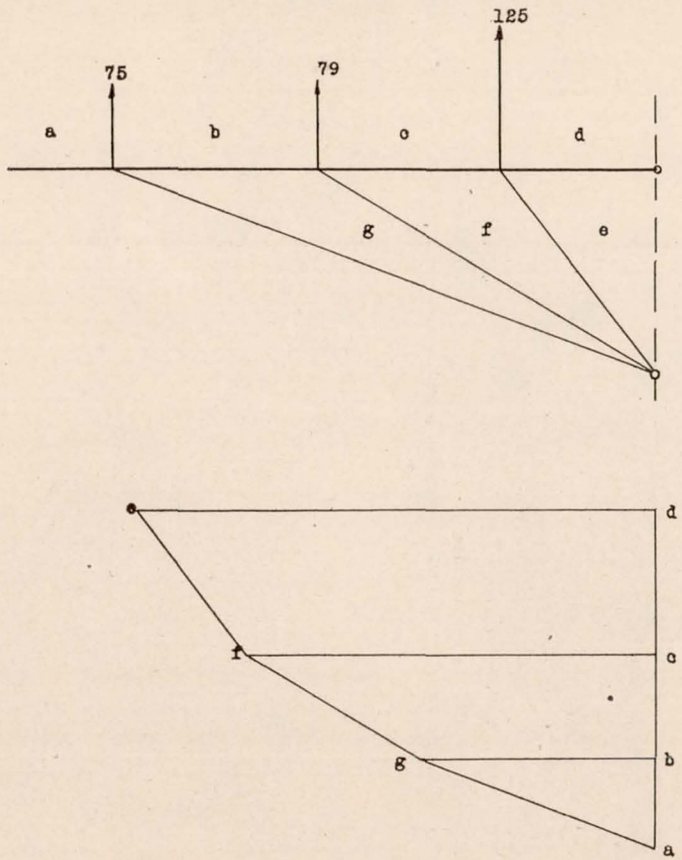
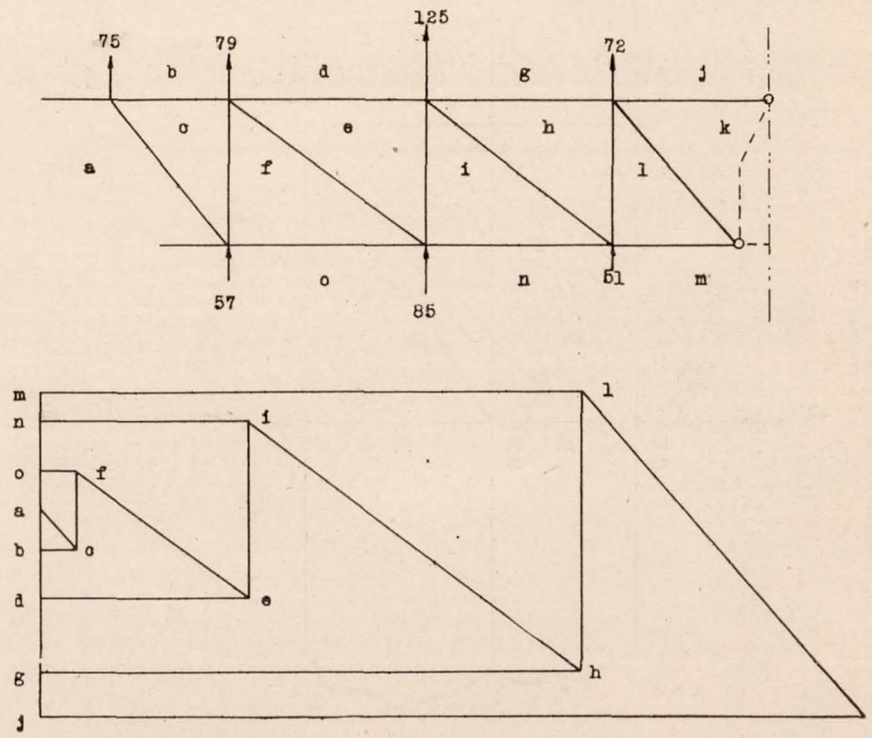


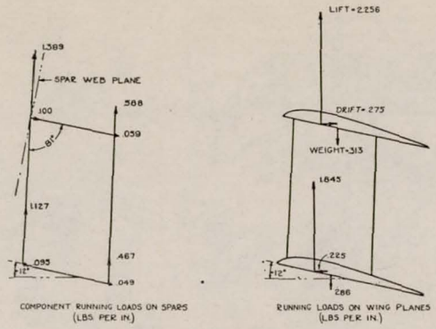
FIG. 27.—Endwise stresses in a biplane wing truss with parallel spars. Graphical treatment.[1]



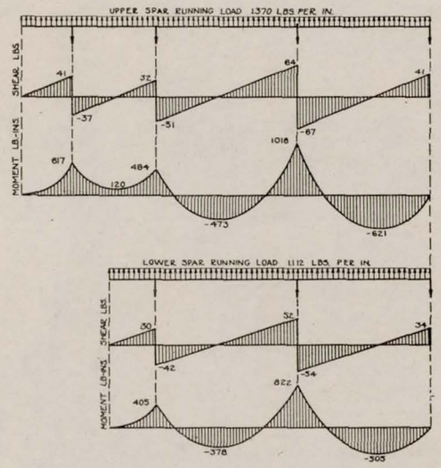
[1] Read anticlockwise.

FIG. 28.

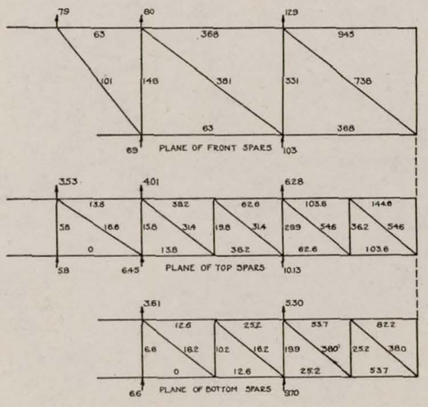
ANALYSIS FOR LOW SPEED – 44 MILES PER HOUR



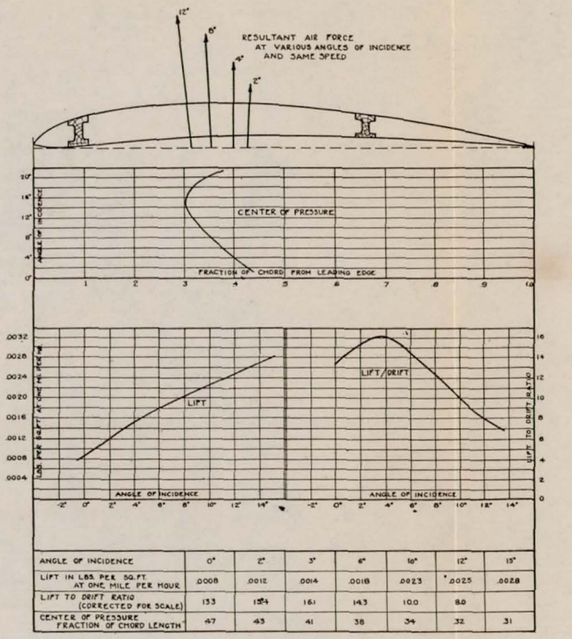
RESOLUTION OF RUNNING LOADS
IN PLANES OF LIFT AND DRIFT TRUSSING



SHEARS AND MOMENTS IN WEB PLANES OF FRONT SPARS

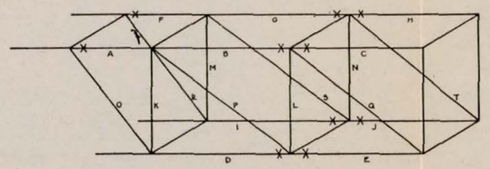


CONCENTRATED LOADS AND ENDWISE STRESSES IN WING TRUSSING



CHARACTERISTIC DATA APPLICABLE AT FULL SCALE AND SPEED
(EIFFEL NO. 36 ASPECT RATIO 6 TO 1, AIR AT 15° CENT AND 760 M.M.)

ANGLE OF INCIDENCE	0°	2°	3°	6°	10°	12°	15°
LIFT IN LBS PER SQ.FT. AT ONE MILE PER HOUR	.0008	.0012	.0014	.0018	.0023	.0025	.0028
LIFT TO DRIFT RATIO (CORRECTED FOR SCALE)	133	154	161	143	10.0	8.0	
CENTER OF PRESSURE FRACTION OF CHORD LENGTH	.47	.43	.41	.38	.34	.32	.31



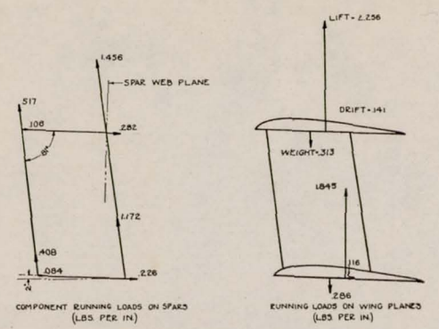
REFERENCE DIAGRAM
(POINTS OF GREATEST STRESS MARKED 'X')

	SYMBOL	MEMBER	MATERIAL	STRENGTH POUNDS PER SQ. IN.	SECTION AREA SQ. INS.	MOMENT OF INERTIA	SECTION MODULUS	FOR LOW SPEED FIBRE STRESS – LBS PER 0" BENDING	LIFT	DRIFT	FACTOR OF SAFETY	FOR HIGH SPEED FIBRE STRESS – LBS PER 0" BENDING	LIFT	DRIFT	FACTOR OF SAFETY
SPARS	A	FRONT SPAR	SPRUCE	4300	2.89	2.82	1.88	±328	24	0	21.2				
	B	"	"	"	"	"	"	±540	140	-15	10.2				
	C	"	"	"	"	"	"	"	360	-24	6.8				
	D	"	"	13000	"	"	"	±437	-24	-5	17.3				
	E	"	"	"	"	"	"	"	-140	-10	14.9				
	F	REAR SPAR	"	4300	3.26	2.32	1.16					±539	20	11	13.2
	G	"	"	"	"	"	"					±918	118	48	6.4
	H	"	"	"	"	"	"					"	303	79	4.8
	I	"	"	13000	"	"	"					±738	-20	17	10.6
	J	"	"	"	"	"	"					"	-118	36	10.0
STRUTS				STRENGTH POUNDS			LENGTH INCHES		LOAD POUNDS				LOAD POUNDS		
	K	FRONT	"	1100	2.89	.279	62.9		148		7.4				
	L	"	"	2800	4.87	.792	"		331		8.4				
	M	REAR	"	1100	2.89	.279	"						154		7.1
	N	"	"	2800	4.87	.792	"						345		8.1
CABLES					NO. OF CABLES	DIAMETER									
	O	FRONT	STEEL	4200	2	1/8			101		41.7				
	P	"	"	6400	"	3/32			381		16.8				
	Q	"	"	"	"	3/32			738		8.6				
	R	REAR	"	4200	"	1/8							106		39.8
	S	"	"	6400	"	3/32							397		16.1
	T	"	"	"	"	3/32							770		8.3

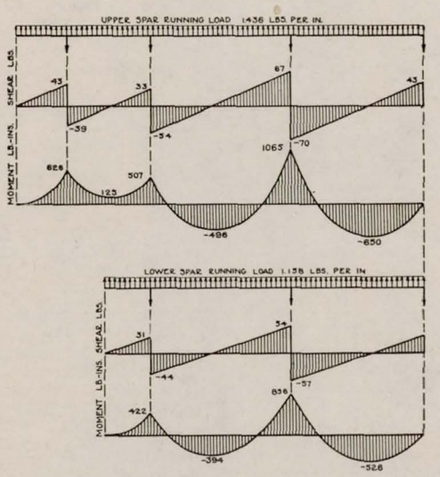
FACTORS OF SAFETY ARE GIVEN FOR POINTS OF GREATEST RESULTANT TENSILE OR COMPRESSIVE STRESS

STRESS ITEMS FOR WING ANALYSIS

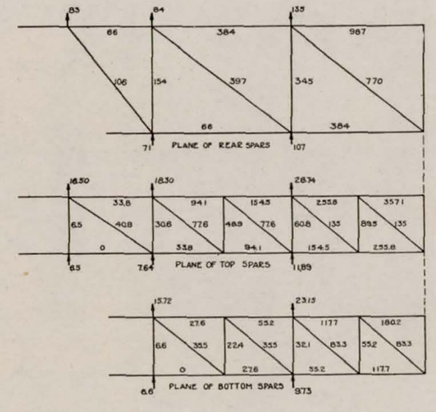
ANALYSIS FOR HIGH SPEED – 75 MILES PER HOUR



RESOLUTION OF RUNNING LOADS
IN PLANES OF LIFT AND DRIFT TRUSSING



SHEARS AND MOMENTS IN WEB PLANES OF REAR SPARS

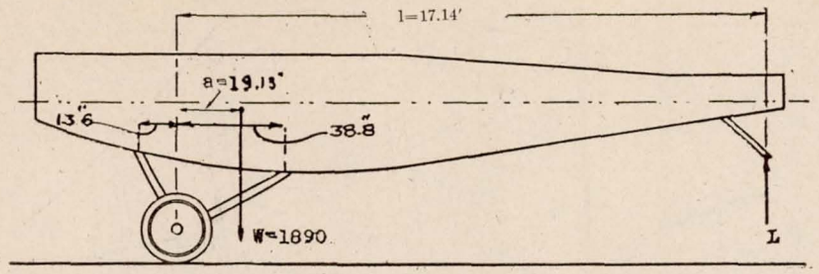


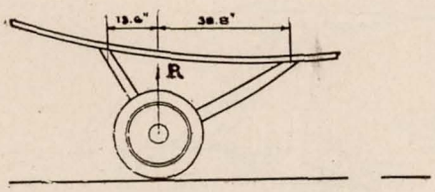
CONCENTRATED LOADS AND ENDWISE STRESSES IN WING TRUSSING

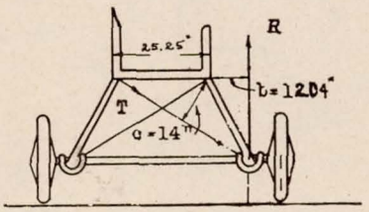
AIRPLANE WING ANALYSIS

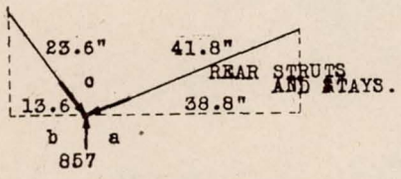
153215—S. Doc. 166, 66–2. (To face page 864.)

FIG. 29.—Graphical analysis for airplane undercarriage.

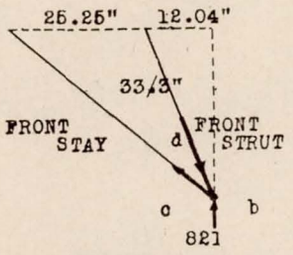




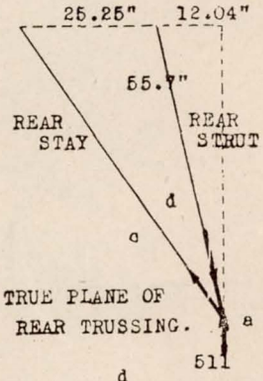




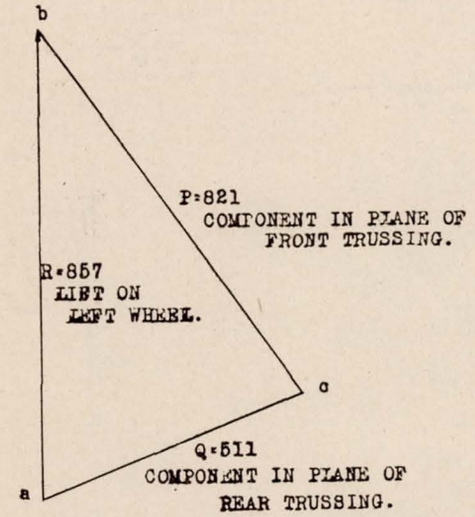
SIDE VIEW OF UNDERCARRIAGE.



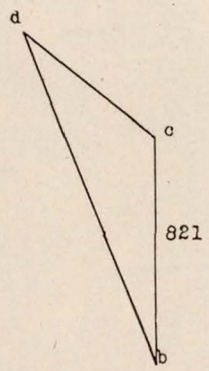
TRUE PLANE OF FRONT TRUSSING



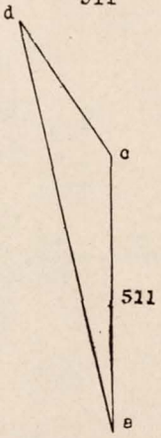
TRUE PLANE OF REAR TRUSSING.



(A) RESOLUTION OF WHEEL LIFT IN PLANE NORMAL TO AXLE.

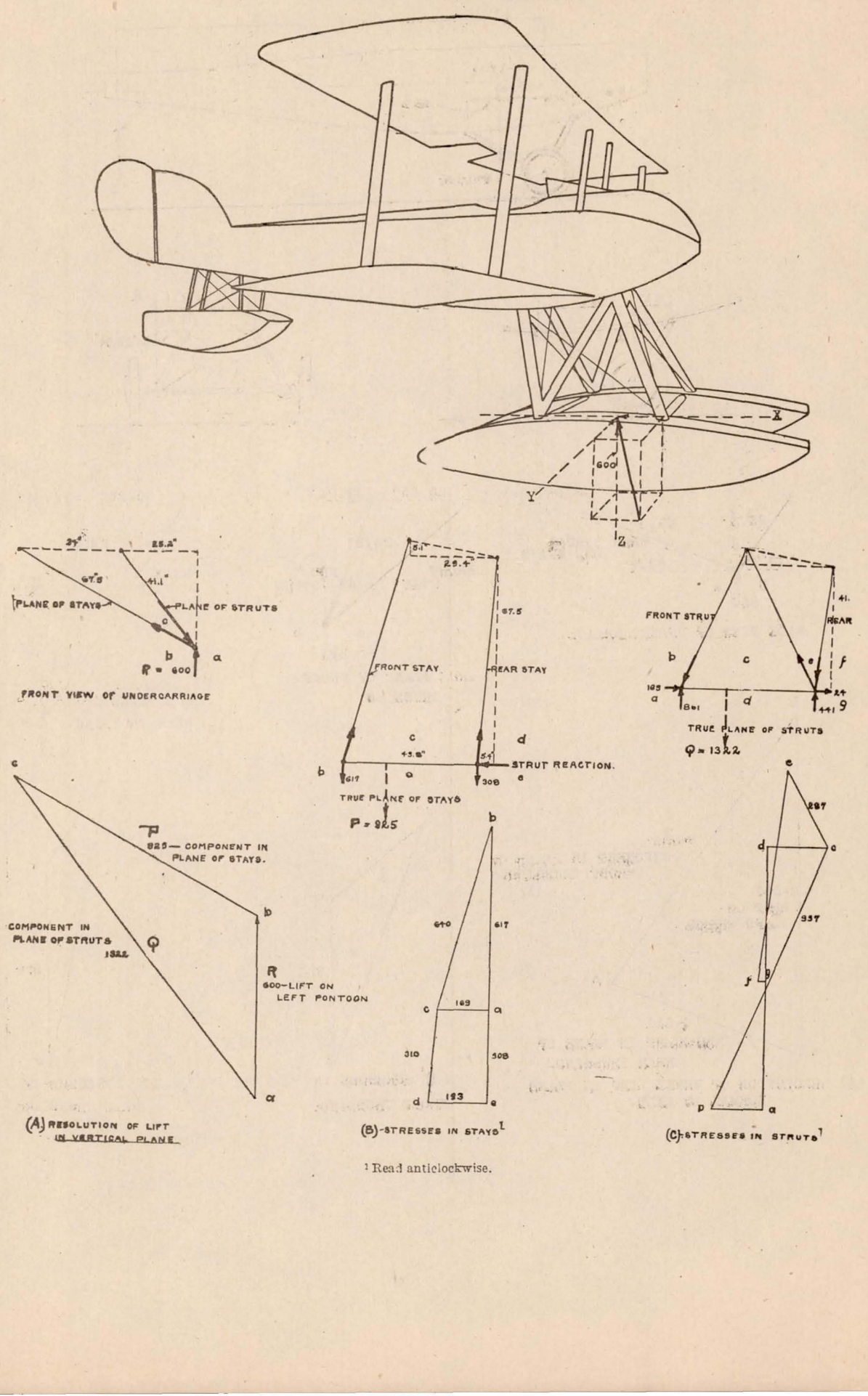


(B) STRESSES IN FRONT TRUSSING.



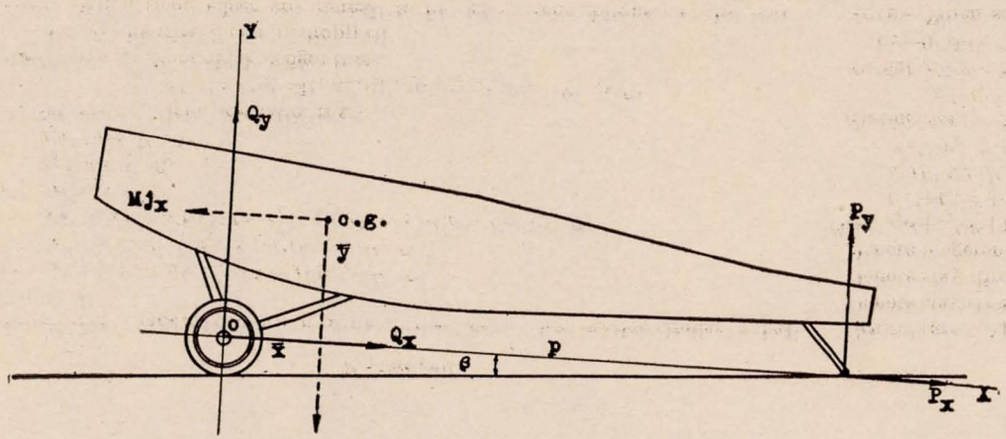
(C) STRESSES IN REAR TRUSSING

FIG. 30.—Graphical analysis for seaplane undercarriage.



[1] Read anticlockwise.

FIG. 31.—Gravitational plus dynamical load on skid and axle.



$M(j_y+g\cos\beta)$

$$P_y = M[+j_y\bar{x}-(j_x y+g\cos\beta\cdot\bar{x})+I_o\alpha]/p$$
$$Q_y = M(j_y+g\cos\beta)-P_y$$
$$P_x = aP_y$$
$$Q_x = bQ_y$$

Where M is mass of craft less wheels and axle,

j_x, j_y are component accelerations of M parallel to X, Y;

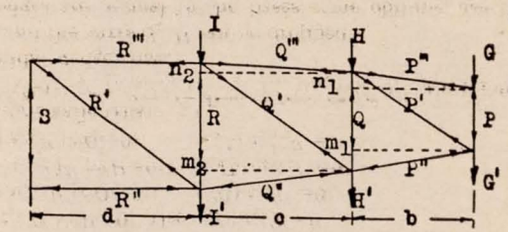
I, α, are the angular inertia and acceleration about the axis o;

$\bar{x}$, $\bar{y}$ are the coordinates of craft centroid referred to o;

p is the distance from skid contact to axle.

NOTE.—If j, j' be the simultaneous vertical accelerations at points on the longitudinal axis l units apart, then $\alpha=(j-j')/l$.

FIG. 32.—Endwise stresses in body trussing with struts vertical and loads concentrated. Analytical treatment.



UPPER LONGERON STRESSES.

$$P'''=0$$
$$Q'''=q_3{}^*(G+G')b/cq$$
$$R'''=r_3[(G+G')(b+c)+(H+H')c]/dr$$
$$S'''=s_3[(G+G')(b+c+d)+(H+H')(c+d)+(I+I')d]/es$$

LOWER LONGERON STRESSES.

$$P''=p_2cQ'''/bq_3$$
$$Q''=q_2dR'''/cr_3$$
$$R''=r_2eS'''/ds_3$$
$$S''=s_2fT'''/et_3$$

STAY STRESSES.

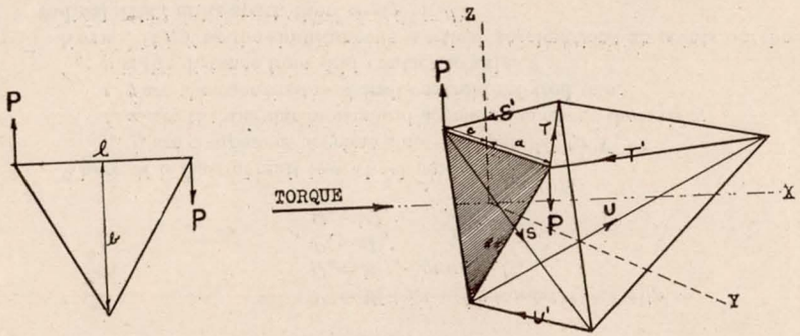
$$P'=p_1[(G+G')-P''n_1/p_2-P'''m_1/p_3]/(q-n_1)$$
$$Q'=q_1[(G+G'+H+H')-Q''n_2/q_2-Q'''m_2/q_3]/(r-n_2)$$
$$R'=r_1[(G+G'+H+H'+I+I')-R''n_3/r_2-R'''m_3/r_3]/(s-n_3)$$
$$S'=s_1[(G+G'+H+H'+I+I'+J+J')-S''n_4/s_2-S'''m_4/s_4]/(t-n_4)$$

STRUT STRESSES.

$$P=G$$
$$Q=H+P'(q-n_1)/p_1+P'''m_1/p_3-Q'''m_2/q_3$$
$$R=I+Q'(r-n_2)/q_1+Q'''m_2/q_3-R'''m_3/r_3$$
$$S=J+R'(s-n_3)/r_1+R'''m_3/r_3-S'''m_4/s_3$$

*q_3, r_2, etc., p_1, q_1, r_1, etc., represent the lengths of the members whose stresses are Q''', R'', etc., P', Q', R', etc., respectively. Interchange m's and n's in Fig. 2.

FIG. 33.—Stresses in twisted pyramidal truss, triangular type.



P=torque/l

General case.—Applied couples in plane of truss base. Use notation similar to that of figure 34.

Then $s_y S+s_y' S'+t_y T+t_y' T'+u_y U+u_y' U'=0$

$s_z S+s_z' S'+t_z T+t_z' T'+u_z U+u_z' U'=0$

$(s_z S+s_z' S')c+(t_z T+t_z' T')a+(u_y U+u_y' U')b+P(a+c)=0$

Also $s_x S+s_x' S'=0$

$t_x T+t_x' T'=0$

$u_x U+u_x' U'=0$

Special case 1.—Right prismatic truss.

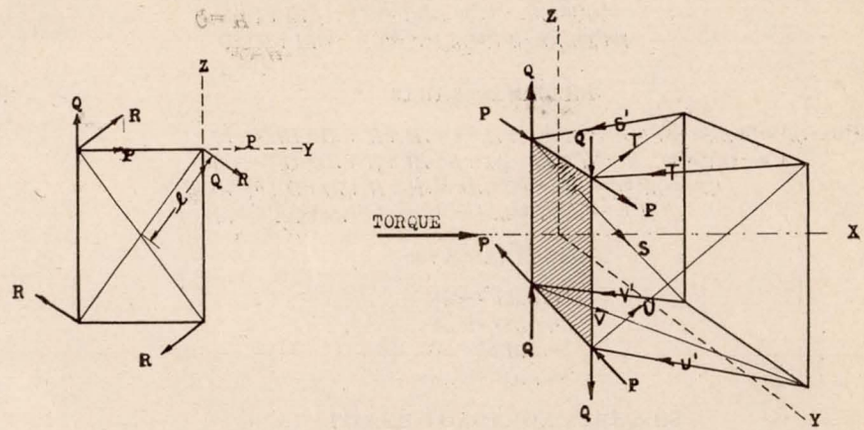
$s_x'=t_x'=u_x'=1$; s_y', t_y', u_y', s_z', t_z', $u_z'=0$; $t_z=0$

Special case 2.—Pyramidal wedge truss.

If $b=0$, the wire U can be dropped.

NOTE.—When some edges are normal to the bases, some oblique, use the more general equations.

FIG. 34.—Stresses in twisted pyramidal truss, rectangular type.



R=torque/4l; $P=Rb/2l$; $Q=Ra/2l$

General case.—Applied couples in plane of truss base.

Denote stay stresses by S, T, U, V; longeron stresses by S', T', U', V'.

Denote stay direction cosines by s_x, s_y, s_z; t_x, t_y, t_z; u_x, u_y, u_z; v_x, v_y, v_z.

Denote longeron cosines by the same letters primed.

Then $s_y S+s_y' S'+t_y T+t_y' T'+2P=0$; Also $s_x S+s_x' S'=0$

$t_z T+t_z' T'+u_z U+u_z' U'+2Q=0$; $t_x T+t_x' T'=0$

$u_y U+u_y' U'+v_y V+v_y' V'+2P=0$; $u_x U+u_x' U'=0$

$v_z V+v_z' V'+s_z S+s_z' S'+2Q=0$; $v_x V+v_x' V'=0$

Special case 1.—Right prismatic truss.

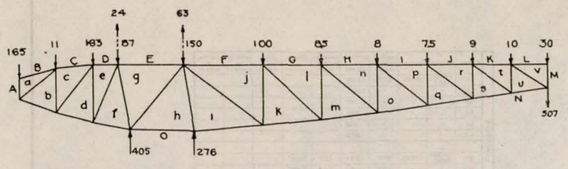
s_x', t_x', u_x', $v_x'=1$; s_y', t_y', u_y', v_y', s_z', t_z', u_z', $v_z'=0$; $s_y t_z u_y v_z=0$

Special case 2.—Pyramidal wedge truss.

If $a=0$, then $Q=0$, and the wires S, U can be dropped.

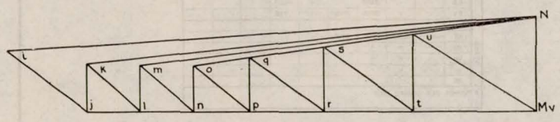
NOTE.—When some edges are normal to the bases, some oblique, use the more general equations.

ANALYSIS FOR STEADY LEVEL FLIGHT

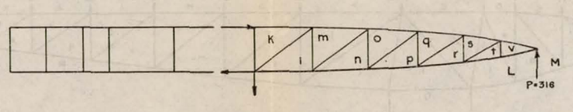


I FUSELAGE WITH VERTICAL AIR LOAD (F) DUE TO 20 LBS PER SQ FT ON HORIZONTAL TAIL SURFACE

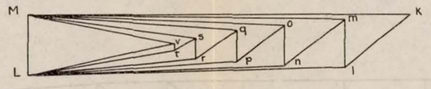
II FUSELAGE WITH VERTICAL GRAVITY LOADS IN STEADY FLIGHT TAIL AIR FORCES OMITTED



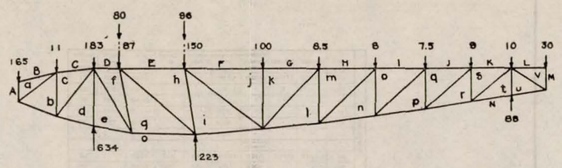
STRESSES FOR I



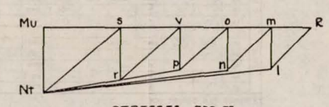
III UPPER TRUSSING OF FUSELAGE WITH PART OF TRANSVERSE AIR LOAD (P) DUE TO 20 LBS. PER SQ.FT. ON VERTICAL SURFACES. ONE HALF OF (P) CARRIED BY UPPER TRUSSING



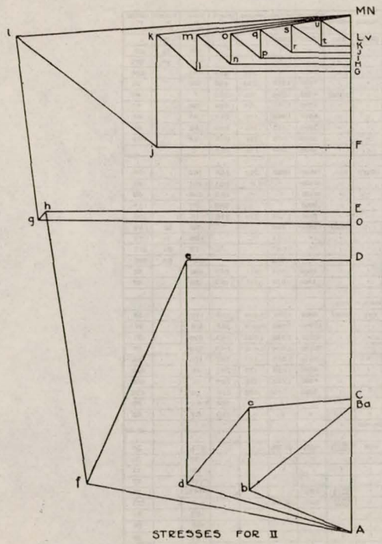
STRESSES FOR III



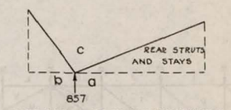
V FUSELAGE WITH TAIL SKID FORCE ONLY
IV FUSELAGE WITH COMPLETE STATIC LOAD



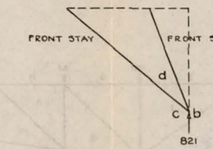
STRESSES FOR V



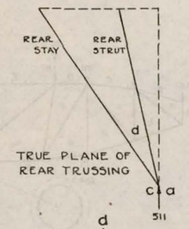
STRESSES FOR II



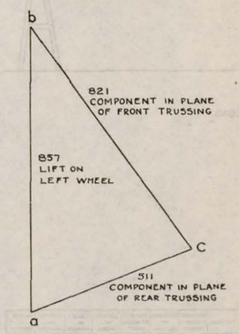
SIDE VIEW OF UNDERCARRIAGE



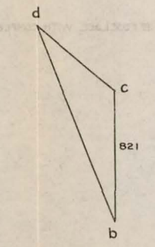
TRUE PLANE OF FRONT TRUSSING



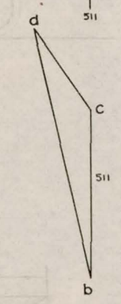
TRUE PLANE OF REAR TRUSSING



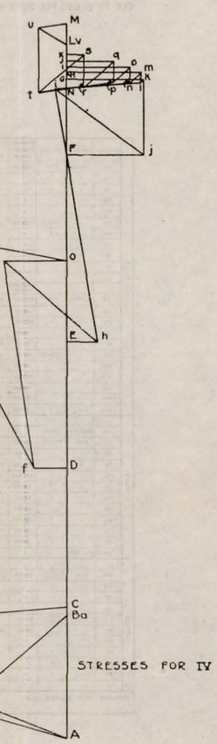
RESOLUTION OF WHEEL LIFT IN PLANE NORMAL TO AXLE



STRESSES IN FRONT TRUSSING



STRESSES IN REAR TRUSSING



STRESSES FOR IV

ANALYSIS FOR LEVEL STATIC CONDITION

ANALYSIS FOR UNDERCARRIAGE

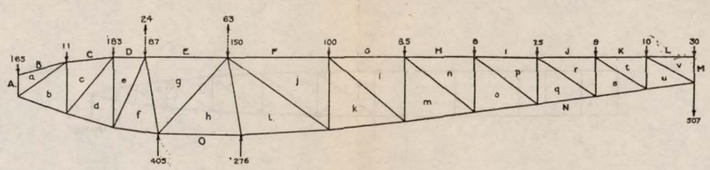
AIRPLANE BODY ANALYSIS

FIG. 36.

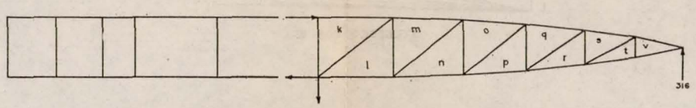
	SYMBOL	MEMBER	MATERIAL	STANDARD STRENGTH POUNDS	SECT AREA IN SQ. INS.	MOMENT OF INERTIA INCHS.⁴	LENGTH IN INCHES	LOAD IN POUNDS	STRESS IN LBS.PER.IN.²	FACTOR OF SAFETY
LONGERONS	G1	UPPER	SPRUCE	13000	1234			-2063	1680	7.7
	Hn	"	"	"	1141			-1769	1530	8.2
	Ip	"	"	"	1.047			-1498	1430	9.0
	Jr	"	"	"	.953			-1113	1165	11.2
	Kt	"	"	"	.859			-643	750	17.3
	Lv	"	"	"	.859			0	0	
				STRENGTH POUNDS						
	Nk	LOWER	SPRUCE	4500	1234	.189	310	2359		1.9
	Nm	"	"	4500	1141	.184	283	2080		1.9
	No	"	"	4000	1.047	.179	263	1808		2.2
	Nq	"	"	3800	.953	.175	243	1514		2.5
	Ns	"	"	3500	.859	.171	207	1125		3.1
	Nv	"	"	3500	.859	.171	193	651		5.3
STAYS	lm	SIDE	SPRUCE	4500	1.265	.135	281	241		18.7
	no	"	"	4600	1.285	.133	254	240		19.1
	pq	"	"	3800	1.000	.083	215	289		13.1
	rs	"	"	"	"	"	180	345		11.0
	tv	"	"	"	"	"	150	406		8.3
STAYS	k1	SIDE	STEEL WIRE	2000	.102" DIA.			-387		5.1
	mn	"	"	"	"			-365		5.4
	op	"	"	"	"			-378		5.2
	qr	"	"	"	"			-481		4.1
	st	"	"	"	"			-383		5.4

* POUNDS PER SQUARE INCH

STRESS ITEMS FOR I-FUSELAGE WITH VERTICAL FORCE (F) DUE TO 20 LBS. PER SQ. FT. ON HORIZONTAL TAIL SURFACES



I FUSELAGE WITH VERTICAL FORCE (F) DUE TO 20 LBS. PER SQ. FT. ON HORIZONTAL TAIL SURFACES
II FUSELAGE WITH VERTICAL LOADS IN STEADY FLIGHT, TAIL AIR FORCES OMITTED



III FUSELAGE WITH TRANSVERSE FORCE (F) DUE TO 20 LBS. PER SQ.FT. ON VERTICAL TAIL SURFACES
(ACTUAL FORCE (F) REPLACED BY EQUIVALENT FORCE AND TORQUE AT STERN CENTER)

	SYMBOL	MEMBER	MATERIAL	STANDARD STRENGTH POUNDS	SECT AREA IN SQ. INS.	MOMENT OF INERTIA INCHS.⁴	LENGTH IN INCHES	LOAD IN POUNDS	STRESS IN LBS.PER.IN.²	FACTOR OF SAFETY
LONGERONS	L1	UPPER LEFT	SPRUCE	12.000	1234					
	Ln	"	"	"	1141					
	Lp	"	"	"	1.047					
	Lr	"	"	"	.953					
	Lt	"	"	"	.859					
	Lv	"	"	"	.859					
	"	"	"	"	"					
	Mk	UPPER RIGHT	SPRUCE	4800	1234	.189	30.87			-
	Mn	"	"	4300	1.141	.184	28.00			
	Mo	"	"	4300	1.047	.179	28.00			
	Mq	"	"	3800	.953	.175	24.00			
	Ms	"	"	3500	.859	.171	20.50			
	Mv	"	"	3500	.859	.171	18.50			
STRUTS	lm	HORIZONTAL	SPRUCE	4650	1.234	.189	23.00			
	no	"	"	3800	.953	.175	21.37			
	pq	"	"	3900	"	"	18.30			
	rs	"	"	3980	"	"	14.25			
	tv	"	"	3600	.859	.171	7.79			
STAYS	k1	HORIZONTAL	STEEL	1200	.051 DIA.					
	mn	"	"	"	"					
	op	"	"	"	"					
	qr	"	"	"	"					
	st	"	"	"	"					

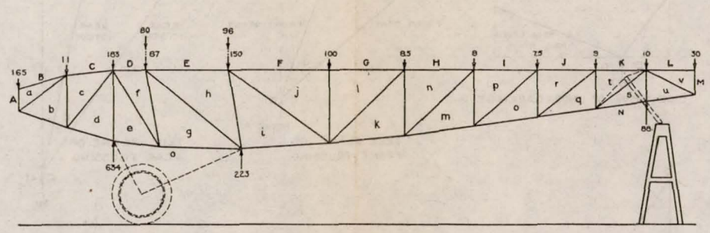
* POUNDS PER SQUARE INCH

STRESS ITEMS FOR III-FUSELAGE WITH TRANSVERSE FORCE (P) DUE TO 20 LBS. PER SQ. FT. ON VERTICAL TAIL SURFACES

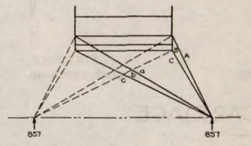
	SYMBOL	MEMBER	MATERIAL	STANDARD STRENGTH POUNDS	SECT AREA IN SQ. INS.	MOMENT OF INERTIA INCHS.⁴	LENGTH IN INCHES	LOAD IN POUNDS	STRESS IN LBS.PER.IN.²	FACTOR OF SAFETY
LONGERONS	Ba	UPPER	ASH	15000*	1880			0	0	
	Cc	"	"	"	"			-134	71	210
	De	"	"	"	"			-214	114	131
	Eg	"	"	"	"					
	Fj	"	"	"	1320			-253	147	102
	Gl	"	SPRUCE	13000*	1234			-2.03	165	78
	Hn	"	"	"	1141			-178	140	93
	Ip	"	"	"	1.047			-130	113	113
	Jr	"	"	"	.953			-78	82	158
	Kt	"	"	"	.859			-38	45	288
	Lv	"	"	"	.859			0	0	
				STRENGTH POUNDS						
	Ab	LOWER	ASH	10500	1880	.332	20.4	144		73
	Ad	"	"	10600	"	"	20.1	222		47
	Af	"	"	10700	"	"	19.5	334		30
	Dh	"	"	9800	"	"	34.0			
	Ni	"	"	8100	1720	.270	37.0	442		18
	Nk	"	SPRUCE	4500	1234	.189	31.0	254		18
	Nm	"	"	4000	1.141	.184	28.3	204		21
	No	"	"	4500	1.047	.179	26.3	160		28
	Nq	"	"	3800	.953	.175	24.3	121		31
	Ns	"	"	3500	.859	.171	20.7	78		44
	Nv	"	"	3500	.859	.171	19.3	39		89
STRUTS	Aq	SIDE PLATE	STEEL							
	bc	SIDE	SPRUCE	6000	1.585	.204	23.6	112		53
	de	"	"	12900	3.080	.681	30.9	302		42
	fg	"	"	10500	2.360	.155	34.3			
	hi	"	"	10200	2.484	.141	34.8			
	jk	"	"	5600	1.362	.203	32.3	149		37
	lm	"	"	4500	1.265	.133	28.1	49		92
	no	"	"	4600	1.285	.133	25.4	41		112
	pq	"	"	3800	1.000	.083	21.5	39		97
	rs	"	"	3800	"	"	18.0	38		100
	tv	"	"	3600	"	"	15.0	34		111
	VM	TAIL POST	"							
STAYS	ab	SIDE	2 STEEL CABLES	4200	1/8" DIA.			-175		24
	cd	"	"	"	"			-131		32
	ef	"	"	"	"			-328		12
	gh	"	"	"	"					
	ij	"	STEEL CABLE	2100	"			-238		8
	Kl	"	STEEL WIRE	2000	.102" DIA.			-89		29
	mn	"	"	"	"			-39		33
	op	"	"	"	"			-53		37
	qr	"	"	"	"			-52		38
	st	"	"	"	"			-49		40
	vv	"	"	"	"			-43		44

* POUNDS PER SQUARE INCH

STRESS ITEMS FOR II-FUSELAGE WITH VERTICAL LOADS IN STEADY FLIGHT, TAIL AIR FORCES OMITTED



IV FUSELAGE WITH COMPLETE STATIC LOAD



V UNDERCARRIAGE WITH STATIC LOADING

	SYMBOL	MEMBER	MATERIAL	STANDARD STRENGTH POUNDS	SECT AREA IN SQ. INS.	MOMENT OF INERTIA INCHS.⁴	LENGTH IN INCHES	LOAD IN POUNDS	STRESS IN LBS.PER.IN.²	FACTOR OF SAFETY
STRUTS	AB	FRONT	SPRUCE	3600		418	333	1307		4.2
	BC	REAR	"	1890		418	357	778		2.3
STAYS	ab	FRONT	CABLE	4700	3/16" DIA.			-820		7.5
	bc	REAR	"	4700	"			-302		15.3

STRESS ITEMS FOR V-UNDERCARRIAGE WITH STATIC LOADING

	SYMBOL	MEMBER	MATERIAL	STANDARD STRENGTH POUNDS	SECT AREA IN SQ. INS.	MOMENT OF INERTIA INCHS.⁴	LENGTH IN INCHES	LOAD IN POUNDS	STRESS IN LBS.PER.IN.²	FACTOR OF SAFETY
LONGERONS	Ba	UPPER	ASH	15000*	1880			0	0	
	Cc	"	"	"	"			-134	72	210
	Df	"	"	"	"			-145	24	623
	Eh	"	"	9400	"	.352	338	+42		224
	Fj	"	"	7400	1.720	.270	418	102		72
	Gl	"	SPRUCE	4500	1.234	.189	30.8	"		44
	Hn	"	"	4300	1.141	.184	28.0	.00		47
	Ip	"	"	4000	1.047	.178	24.0	84		47
	Jr	"	"	3800	.953	.175	24.0	82		61
	Kt	"	"	3500	.859	.171	20.3	24		145
	Lv	"	"	3500	.859	.171	18.3	0		
	Ab	LOWER	ASH	10500	1.880	.352	20.4	142		74
	Ad	"	"	10600	"	"	20.1	222		47
	Oe	"	"	10700	"	"	18.5	216		49
	Og	"	"	9800	"	"	34.0	84		114
	Ni	"	"	8100	1.720	.270	37.0	18		500
	Nk	"	SPRUCE	13000*	1.234			-85	80	162
	Nm	"	"	"	1.141			-84	74	175
	No	"	"	"	1.047			-83	61	215
	Nq	"	"	"	.953			-24	28	500
	Ns	"	"	3500	.859	.171	20.7	4.38		92
	Nu	"	"	3500	.859	.171	19.3	36		92
STRUTS	Aq	SIDE PLATE	STEEL							
	bc	SIDE	SPRUCE	6000	1.585	.204	23.6	112		53
	de	"	"	12900	3.080	4.610	30.9	812		21
	fg	"	"	10500	2.360	1.830	34.3	278		37
	hi	"	"	10200	2.484	1.410	34.8	334		30
	jl	"	"	5600	1.362	.203	32.3	100		38
	kn	"	"	4500	1.265	.133	28.1	14		320
	mp	"	"	4600	1.285	.133	25.4	22		208
	or	"	"	3800	1.000	.083	21.5	28		135
	qt	"	"	"	"	"	18.0	44		86
	sw	"	"	"	"	"	15.0	87		43
	vM	TAIL POST	"							
STAYS	ab	SIDE	2 STEEL CABLES	4200	1/8" DIA.			-173		24
	cd	"	"	"	"			-132		31
	ef	"	"	"	"			-336		11
	gh	"	"	"	"			-168		25
	ij	"	STEEL CABLE	2100	"			-142		14
	Kl	"	STEEL WIRE	2000	.102 DIA.			- 6		333
	mn	"	"	"	"			-22		91
	op	"	"	"	"			-30		66
	qr	"	"	"	"			-31		39
	st	"	"	"	"			-81		24
	vv	"	"	"	"			-43		44

* POUNDS PER SQUARE INCH

STRESS ITEMS FOR IV-FUSELAGE WITH COMPLETE STATIC LOAD

AIRPLANE BODY ANALYSIS

FIG. 37.—Specifications for typical tail unit.

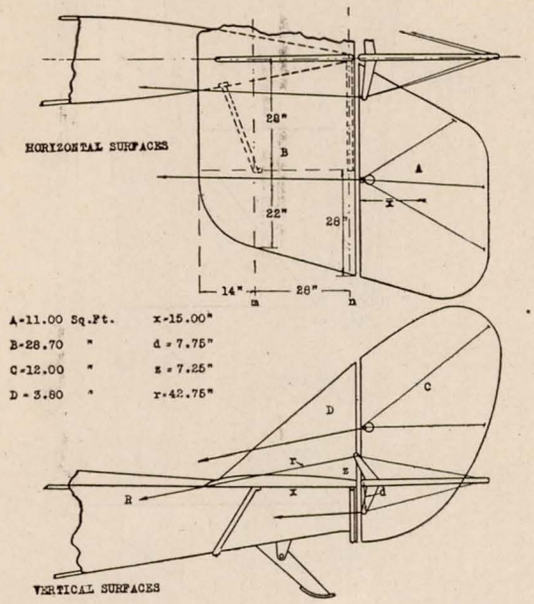
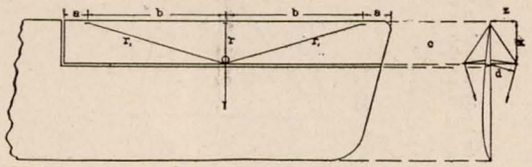
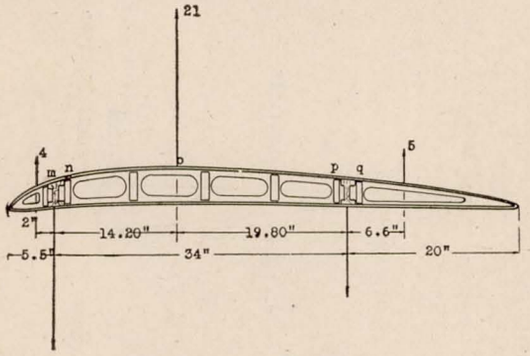


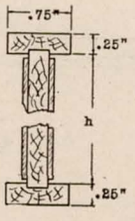
FIG. 38.—Specifiations for typical aileron and connections.



Area A-20.7 Sq.Ft. a-11'' b-70'' c-18.75''
d-12.75'' x-18.75'' z-13.37'' r-22.72'' r-61.78

FIG. 39.—Specifications for typical wing rib.





SECTION	HEIGHT h
m	3.36
n	3.60
o	4.10
p	3.10
q	2.90

FIG. 40.—Specifications for typical biplane wing trussing.

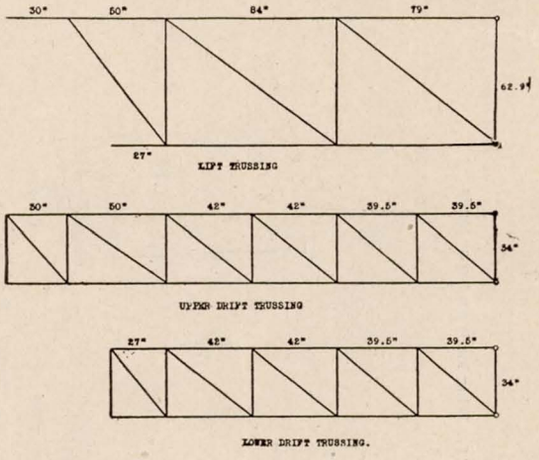
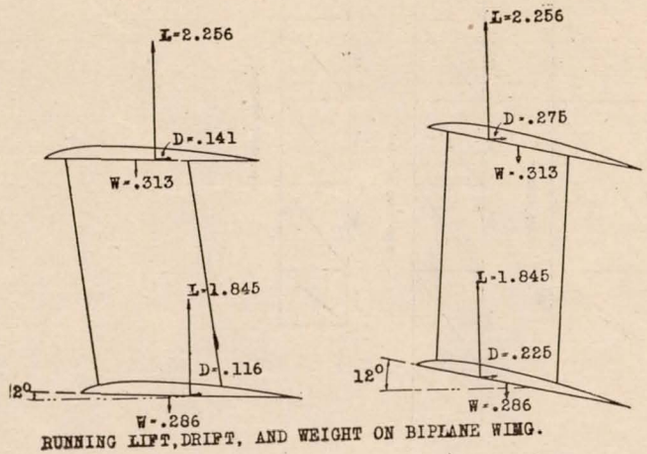


FIG. 41.—Wing loads and spar loads.



RUNNING LIFT, DRIFT, AND WEIGHT ON BIPLANE WING.

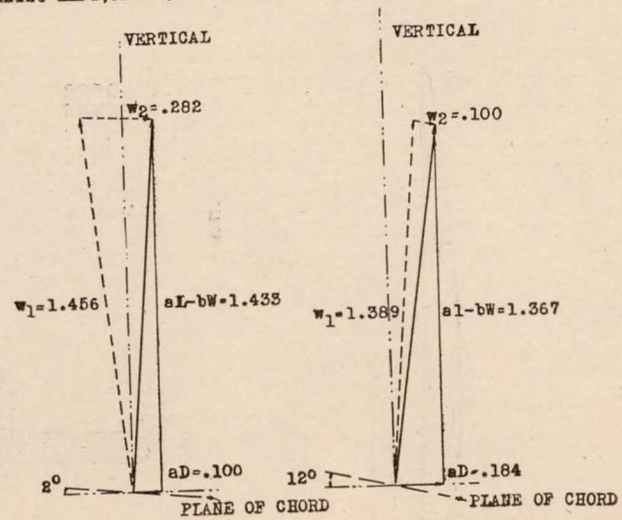
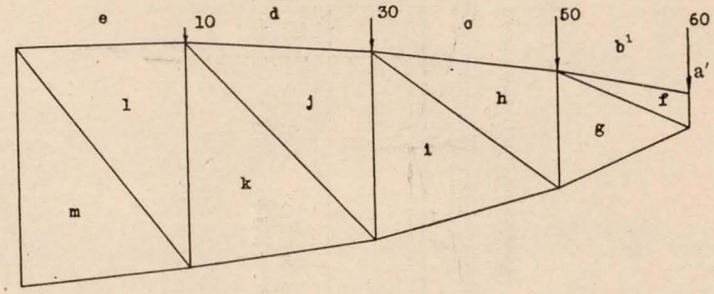
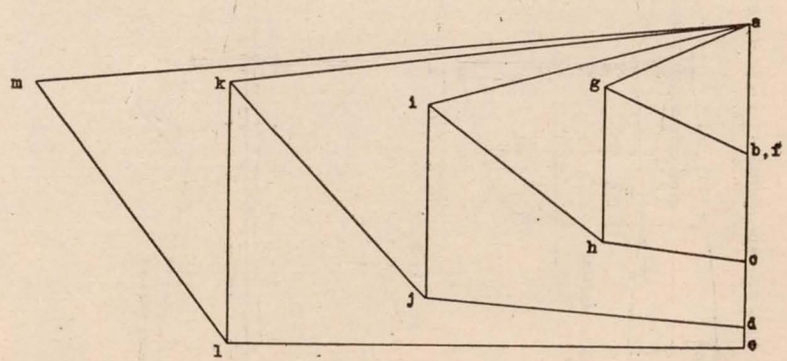


FIG. 42.—Endwise stresses in body trussing with struts vertical and loads concentrated. Graphical treatment.





[1] Read anticlockwise.